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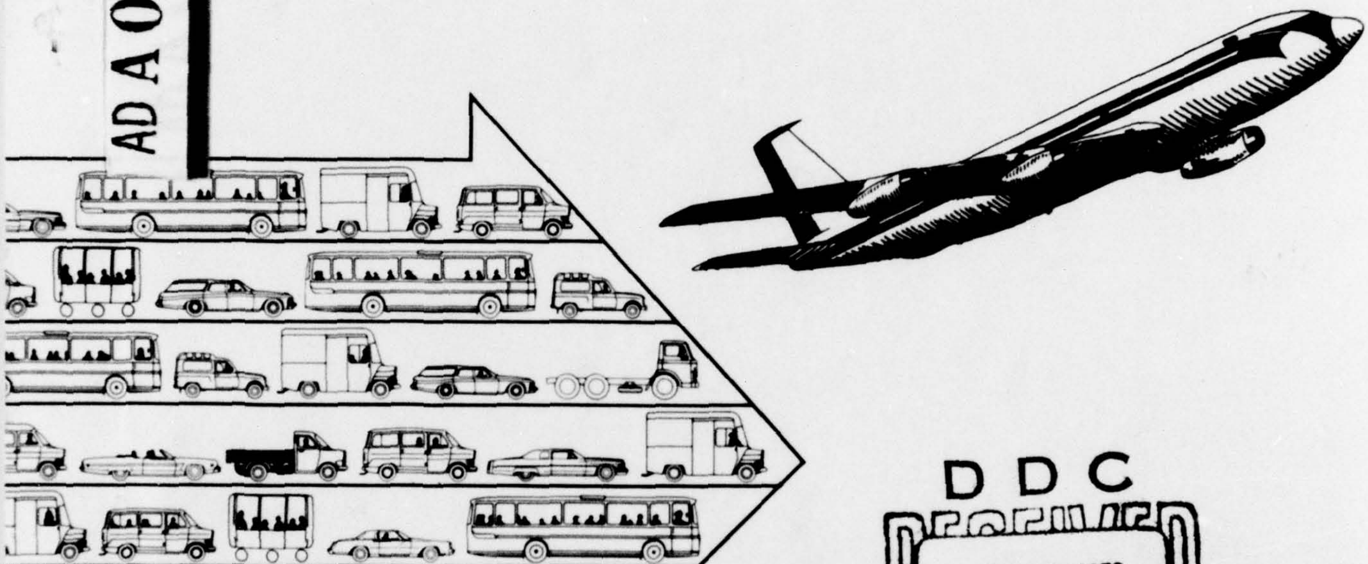

THE F.A.A.'s AIRPORT LANDSIDE MODEL

Analytical Approach to Delay Analysis

JANUARY 1978

DEPARTMENT OF TRANSPORTATION • UNITED STATES OF AMERICA

U.S. DEPARTMENT OF TRANSPORTATION
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16. Abstract Computer implemented analytic models have been developed which will assist in the quantitative assessment of the adequacy of the airport landside; that is, the portion of the airport property not utilized by aircraft. The primary measures of adequacy are passenger delay and passenger processing time. Detailed analytic models have been derived using queuing theory for those airport landside components which are essential to passenger processing. Also, a landside analysis program has been developed to quantify airport landside delay and capacity. The major outputs of this program are the per passenger processing times and cumulative processing times at each terminal unit and groundside area in an airport for both enplaning and deplaning passengers, and a summary of the delay and total processing times at an airport by terminal and for the entire airport. Processing time is separated into delay, service, and travel time. This program has been applied to the existing and planned facilities at the large hub air carrier airports and a large data base has been created for these large hub airports. The data base is constructed so the data can be modified or additional data input can be made in a relatively straightforward manner.

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FOREWORD

This report reflects the work performed under Contract DOT-FA76WAI-643 with the Federal Aviation Administration, Office of Aviation Policy, Mr. William R. Fromme, Technical Monitor, and Mr. Glenn Strahs, Landside Analyst. H. H. Aerospace Design Co., Inc., Bedford, Massachusetts takes this opportunity to acknowledge major contributions towards the accomplishment of the work tasks provided by personnel of Aerospace Systems, Inc., Burlington, Massachusetts. Professor Amedeo R. Odoni of the Aeronautics and Astronautics Department of the Massachusetts Institute of Technology acted as a consultant to the project team and played an important role in the development of some of the analytic models contained herein. The authors would also like to acknowledge Charles Theobold for his assistance in the model development in this study.

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SECTION 1

INTRODUCTION AND OVERVIEW

A brief introduction to the problem, including an historical overview of airport modeling development, is presented in this section. A description of the format and content of this report is also included.

1.1 INTRODUCTION

Recent airport capacity studies (e.g., References 1 and 2) have indicated that there is an imbalance in airport landside and airside planning at many major airports. As used here, "landside" refers to that portion of the airport property not utilized by aircraft. Traditionally, the emphasis has been on airside development and analysis. Although there is no generally accepted method to quantitatively assess the adequacy of the airport landside, several studies have been conducted on the airport landside problem. Examples include airline studies (References 3, 4, and 5), general planning guidelines (References 6 through 9) and airport simulation models (References 10 through 13). Such studies are particularly important since in many cases around the world, some aspects of landside operations have become major congestion problems as the number of air passengers continues to increase.

The purpose of this study is to develop a tool in the form of computer implemented analytic models which will assist in the quantitative assessment of the adequacy of the airport landside. The primary measures of adequacy are passenger delay and passenger processing time. Detailed analytic models have been derived for those airport landside components which are essential to passenger processing. Also, a methodology has been developed to quantify airport landside delay and capacity; this methodology has been applied to the existing and planned facilities at the large hub air carrier airports and a large data base has been created. The results of this study should assist airport operators and planners in determining the requirements of landside improvements.

1.2 POSSIBLE TYPES OF AIRPORT LANDSIDE MODELS

The aims of this study can be put into better perspective by reviewing briefly the possible types of airport landside models. It will be assumed that the purpose of these models is twofold: first, to provide the means for evaluating the level of service offered by existing facilities and, as a consequence, to assist in determining the need for -- and potential benefits that would result from -- expansion of these facilities; and, second, to serve as tools in setting the design specifications for new terminal (and, in general, groundside) facilities.

Classification of model types will be made with respect to the extent to which these models recognize and deal explicitly with the two essential characteristics of airport landside demand: <u>time-variation</u> and <u>stochasticity</u>. Concerning time-variation, it is well known that demand for the use of the various components of an airport's landside system is strongly dependent on the time of the day (and is also influenced by day of the week and by seasonal factors). As to the stochasticity, it is also clear that, in addition to time-variations in the demand rates, there are also random fluctuations in airport demand from day to day and from hour to hour. In summary, demand for use of airport landside facilities is both probabilistic and time-varying.

At the simplest level of modeling ("level I" models) neither of these two characteristics of airport demand is explicitly taken into account. Level I models generally consider only the <u>peak hour demand</u> (in terms of the appropriate units, e.g., number of passengers or number of pieces of luggage or number of cars, etc.) at each part of the airport landside. This peak hour demand thus serves as the basic design input for each component of the landside system: the airport planner, designer or administrator attempts to provide sufficient service capacity at each of these components to be able to satisfy this maximum demand rate. Obviously, level I models are of little help in evaluating the level of service provided by existing facilities and the need for facility expansion: with no random fluctuations in demand and with the service capacity assumed to be always in excess of even the maximum demand rate, delays for access to the various services are equal to zero.

Level I models are typically those used by architects and civil engineers in the design of new terminals and groundside facilities. The airport is designed for some future peak hour on the basis of such models and of some empirical formulae. Unfortunately, these designers do not often recognize the fact that serious groundside congestion problems (due to time variations and randomness of the demand and service times)

may be present even when the average demand rates are well below the design capacities of their buildings and service facilities.

A more sophisticated type of model ("level II" model) is the one that considers explicitly the time-variations in the average demand rate at an airport. As a result, it is recognized that whenever the average demand rate at a given component of the landside system exceeds the maximum service rate for that component, a queue (or queues) will be created and delays will be incurred.

Several investigators (e.g., References 14 and 15) have presented such level II models since the mid-1960s, including a recent effort (Reference 16) to consider all terminal building services from this point of view. Unfortunately, it is obvious that level II models are deficient in the following respect: as long as the average demand rate is below the maximum service capacity at a component of the airport complex, these models estimate no delays or congestion at the airport, even when the average demand is just below the maximum service capacity. However, as is well known from queuing theory, whenever random fluctuations are present either in the arrival process or for the service times at a service facility, considerable and often unacceptable delays may occur even when, on the average, demand is well below the maximum service capacity.

Levels III and IV models would account for such situations by considering explicitly the probabilistic aspects of airport demand and airport service rates. We define a level III model as one which is based on steady-state queuing analysis. In other words such a model assumes that: 1) for any given period of time, the average rate of demand at each airport landside component and the average rate of service at each component remains constant, but with random fluctuations described by probabilistic processes, and 2) each time period is long enough so that statistical equilibrium (steady-state) can be reached at the landside system component of interest.

By contrast, a level IV model is defined as one for which the demand arrival process and the service process can both be: 1) probabilistic; and 2) time-varying (in the sense that the average rate of demand and the average rate of service at each component of the landside system can be explicit functions of time). Obviously, level IV models can be said to be at the highest theoretical level of sophistication possible, but it is an inappropriate and impractical level for current landside modeling programs.

The work presented in this report is aimed at developing level III models for all the components of the airport landside complex. Thus, these models attempt to consider explicitly the probabilistic properties and random fluctuations of the demand arrival process and of the service processes at the major airports. The models use the tools of queuing theory to obtain estimates of the delays that air passengers and airport visitors suffer due to these fluctuations.

In addition, the models use a simple, straightforward approximation formula (see Subsection 3.3.1) for estimating delays for those periods of time when the average demand rate exceeds the maximum service rate at any given component of the landside system. Consequently, the approach taken here also incorporates the analytical potential provided by the level II models that were described above.

To the best of the authors' knowledge, this is only the second effort to develop such level III models for the entire airport landside complex (the first being the very recent work of Parraras, Reference 17, which, however, dealt with the terminal buildings only and had somewhat different objectives than the present study). Since the project team was working in what is in effect a vacuum of earlier work (for many of the components of the airport) some of the models developed can be considered only as "first cuts" at obtaining initial approximations for quantities of interest (i.e., level-of-service characteristics). It is believed, however, that the overall structure of the analysis, and especially the network framework within which it was placed (see Subsection 3.4), is a sound one and can provide the "building base" for further development. It is, therefore, hoped that other investigators will have an opportunity to continue this work, particularly with respect to strengthening some of the queuing models. As will be explained in Section 4, the computer programs are written in a modular way that facilitates substitution of a queuing model for any given landside component by a superior one, whenever such a model becomes available.

Consideration was also given to making an attempt to develop level IV models for the airport landside. Such a model was first presented for the airport airside in 1972 (Reference 18) and was considerably generalized and subsequently strengthened (References 19 and 20). Unfortunately, the airport landside problem is considerably more complex than the airside one due to: 1) the large number of system "components" (e.g., roadway, parking, curbside, ticket counters, security processing, seat assignment, etc.); 2) the much larger number of units (i.e., people, cars, pieces of luggage) that must be processed. The latter number is of the order of thousands per hour (as opposed

to the 50 to 150 aircraft that are processed per hour at the airside of a typical major airport). Because of these two difficulties, it was deemed that the present state-of-the-art in analytical techniques for time-dependent queuing systems made it infeasible to develop (within the time and budgeting constraints of this study) any level IV models at this stage.

1.3 REPORT FORMAT

The previous subsections have presented an introduction and historical background and overview of airport landside studies. Section 2 continues with a description of the approach used in this study. Included is a more detailed specification of the problem, the major assumptions, data requirements and the specific methodology used. The theoretical development is contained in Section 3, in which the equations and algorithms used in the programs for the models are presented. A flow description and sample outputs of the program are contained in Section 4. Section 5 presents a summary of the study and recommendations for future analyses.

SECTION 2
STUDY APPROACH

A description of the study and analysis techniques is included in this section. First, the specification of the problem and the general approach taken are described. The major assumptions and approximations are also noted. The landside elements of interest in this study are described together with the network identification techniques. The specific approaches developed and implemented in the computer programs are also outlined.

2.1 PROBLEM SPECIFICATION

An airport serves as an interface between ground transportation and air transportation. As shown in Figure 2-1, the airport system naturally divides into three major sections: airside, terminals, and groundside. Each section is characterized by a different type of flow. The airside is the section of the airport used by aircraft. The terminal is that part of the airport characterized by the flow of passengers (and baggage); the groundside is described primarily by vehicle flows. For this study the terminal and groundside sections of the airport are referred to together as the airport "landside."

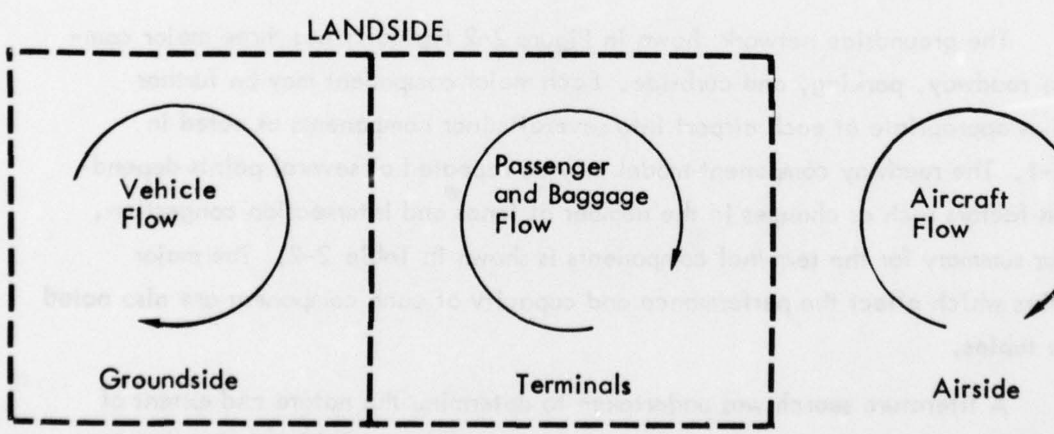

FIGURE 2-1. AIRPORT SYSTEM FLOWS.

The airport landside can be further divided into components, with each component associated with a particular passenger service, such as check-in and baggage claim. Furthermore, these components fall into two major categories. First, there are those items such as auto parking, check-in and security inspection which are essential items for passenger processing. Second, there is a class of services which is a necessary part of the airport system, but which is not essential for passenger processing. Examples of these components are restrooms, telephones and concessions. Only the services which are essential for passenger processing are of interest in this study.

A sample airport groundside network which identifies several of the components of interest is shown in Figure 2-2. A similar diagram of the terminal components is shown in Figure 2-3. These figures serve the dual purpose of identifying typical components in the airport landside and specifying the branch flows and flow rates which are required. Note that the particular components which apply and the network linking the components will most likely vary from airport to airport. This applies both to the groundside where the network is described primarily by the roadway system, and to the terminal where the network is usually associated with the terminal geometry (location and number of concourses, security checkpoints, etc.). Thus the problem of determining passenger delays in the airport landside divides into 1) specifying the particular landside components which apply, and 2) identifying the network and network flows which link the components.

The groundside network shown in Figure 2-2 typically has three major components: roadway, parking, and curbside. Each major component may be further divided as appropriate at each airport into several minor components as noted in Table 2-1. The roadway component model may be repeated at several points depending upon factors such as changes in the number of lanes and intersection congestion. A similar summary for the terminal components is shown in Table 2-2. The major parameters which affect the performance and capacity of each component are also noted in these tables.

A literature search was undertaken to determine the nature and extent of previous related studies. Included at the end of this report is a bibliography that includes a number of airport landside model development efforts which have been identified. These include programs by Battelle, TAMS, Bechtel, MIT, and others. The applicability of these models to this study is minimal, however, for the following

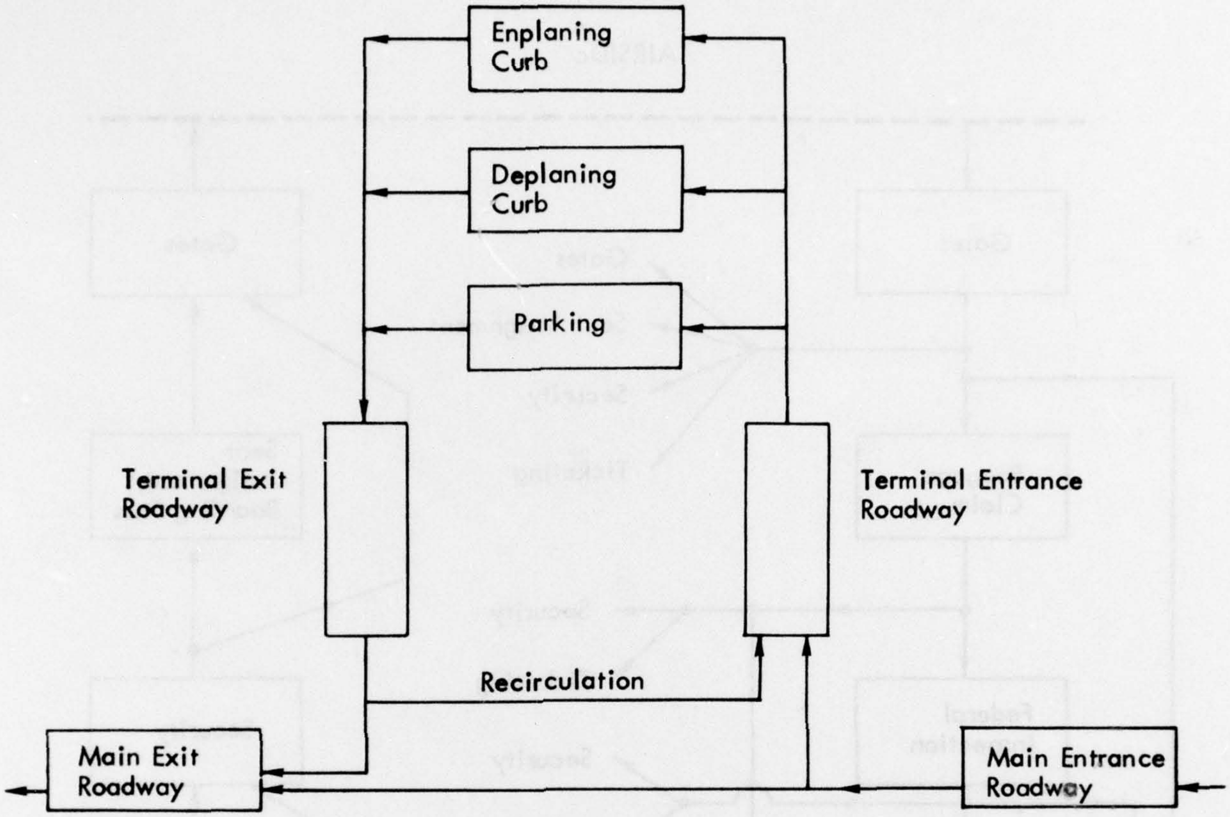

FIGURE 2-2. TYPICAL AIRPORT GROUNDSIDE NETWORK.

reasons. First, most of the above models have been developed for a particular airport or airport concept; in this study a general model, applicable to any air carrier airport is desired. Also, most of the models are simulation programs which use random number generators in a "Monte Carlo" approach to system studies; in this study analytic models are desired which eliminate the need for multiple computer runs. A search was also made in the various operations research and technical journals for studies on development of particular landside component models. Several articles have been located, and are included in the bibliography. These articles have been particularly useful in the component model development, as noted in Section 3.

2.2 GENERAL APPROACH

The methods which are used to quantify airport landside capacity and delay are discussed in this section. First, the major objectives of the study are restated and the main program assumptions, inputs, output and control variables are specified.

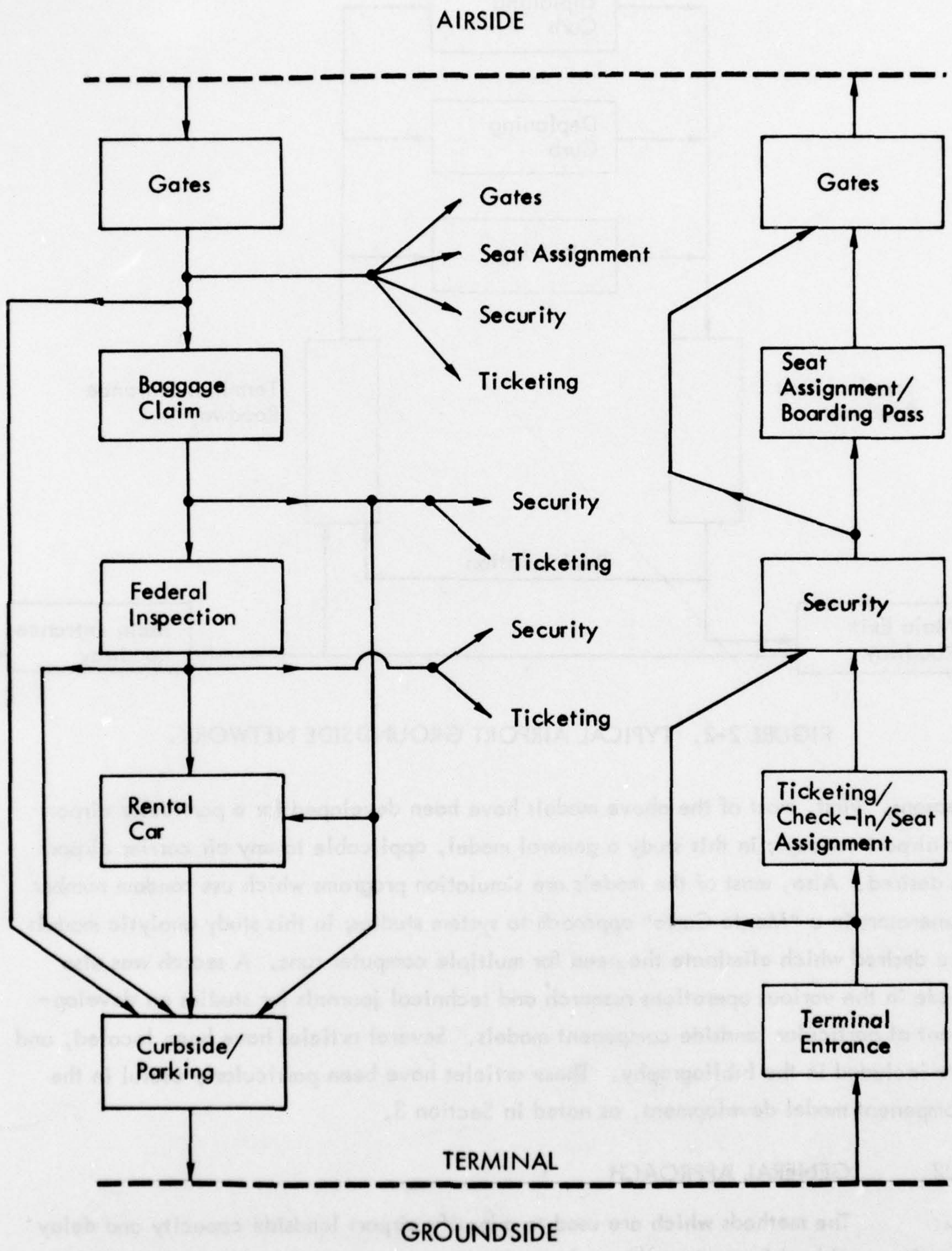

FIGURE 2-3. TYPICAL AIRPORT TERMINAL NETWORK.

TABLE 2-1. AIRPORT GROUNDSIDE COMPONENTS.

Major Component	Subcomponents	Major Parameters
Roadway	–	Number of Lanes Average Speed Intersections Vehicle Mix Passengers per Vehicle Length of Roadway
Parking	Long Term	Spaces Available Average Length of Stay in Lot
	Short Term	Spaces Available Average Length of Stay in Lot
	Rental Car	Number of Servers Service Time, Discipline Transportation Mode to Terminal
Curbside (vehicle)	Enplaning	Curb Length Number of Terminal Doors Number of Lanes Vehicle Mix Passenger/Visitor Ratio Number of Bags/Passenger Share with Deplaning (Yes/No) Passenger Per Vehicle Type
	Deplaning	Curb Length Number of Terminal Doors Number of Lanes Vehicle Mix Passenger/Visitor Ratio Number of Bags/Passenger Share with Enplaning (Yes/No) Passenger Per Vehicle Type

TABLE 2-2. AIRPORT TERMINAL COMPONENTS.

Major Component	Subcomponents	Major Parameters
Curbside (passenger)	-	Enplaning/Deplaning Separate (Yes/No) Number of Doors Bags/Passenger
Ticketing	Full Service Information Only Baggage Check-In Seat Assignment	Number of Servers Service Time/Discipline Number of Bags Service Used Skycaps, Assistants (Yes/No)
Security	-	Manual or X-Ray Carry-on Bags/Passenger Series Servers (Yes/No) Number of Servers Passenger/Visitor Ratio
Seat Assignment	Boarding Pass Seating Assignment	Number of Check-In Servers Geometry
Baggage Claim	-	Equipment Type/Capacity Bags/Passenger Number of Units Positive Claim (Yes/No) Distance from Arrival Gate
Federal Inspection	Customs Health Immigration	Number of Servers Bags/Passenger Service Time Discipline Series Servers (Yes/No)
Rental Car	-	Number of Servers Reserved Car (Percent) Manual/Machine Transportation Type to Ready Car/ Drop-off Area

Throughout this study, the passenger delay time refers to the excess time spent in the system due to congestion, waiting in line, etc. The service time is the time spent at a facility regardless of any delay. At ticketing, it would represent the time spent checking in baggage, for example, once at the head of the line. The travel time is the time spent walking or driving between service facilities. It is a function mainly of the distance between the facilities and the average traveling speed.

Broadly stated, the goal of this study is to develop a tool to quantitatively assess the level of service for the airport landside. The level of service is measured primarily by passenger delays and passenger processing times. The "tool" consists of a set of computer routines which analytically models each component or subcomponent of the airport landside and a program and methodology for linking the routines as appropriate for any air carrier airport to compute the level of service. The primary input variable is the number of peak hour (or any design hour) enplaning and deplaning passengers.

Other input variables include passenger modal split, bags per passenger, percentage of connecting passengers, and passengers per vehicle type. A summary of the basic approach and program inputs and outputs is presented in Table 2-3. Thus, the program will be able to address such questions as the following: How will landside congestion and delay change if the passenger modal split varies? If a policy is implemented to discourage carry-on baggage how much will this affect ticket counter and security checkpoint congestion? Will a particular redesign or expansion of the terminal building or roadway network significantly affect the airport landside? How will the capacity and delay change as the number or type of passengers change? Where are the landside bottlenecks, if any?

Since many factors such as quality and comfort are not easily quantified, the program cannot completely answer all of these questions. It should, however, be of considerable aid to their understanding. Also, other studies can be initiated using this program, such as determining the relative efficiencies of terminal types (e.g., linear, pier, satellite) for different airport categories (connecting, international, short/long haul, etc.).

2.3 MAJOR ASSUMPTIONS

The basic approach used in this analysis is noted in Table 2-3. An understanding of the major assumptions, however, is required to fully appreciate the capabilities and limitations of the programs.

TABLE 2-3. STUDY APPROACH AND PROGRAM INPUT/OUTPUT.

Basic Approach

- Analytic models of each landside component will be used.
- Delay, congestion and capacity will be determined for the Peak Hour (or any design hour).
- Steady-State queuing theory will be used whenever possible. (Time of day variations will not be included.)
- Annual Passenger Delay will be estimated from the number of peak hours in a day and the number of such days each year (rather than through an hour by hour simulation).

Exogenous Inputs

- Annual passenger enplanements.
- Peak or design hour passengers (primary input).
- Passenger modal split.
- Percentage of connecting passengers.
- Baggage carried per passenger.
- Aircraft fleet mix, load factor and operations.
- Passengers/vehicle by vehicle type.

Airport Inputs

- Physical - numbers and sizes of components, geometry of terminal, location of elements, distances between components.
- Passenger Ratios - connecting/originating, domestic/international, passenger/visitor.

Program Outputs (Airport Total and Component)

- Delays.
- Service times.
- Travel (walking, driving) times.
- Passenger and vehicle flow rates.
- Saturation points and congestion locations.

The most important simplifying assumption is that steady-state conditions are achieved during the peak (or design) hour. As a result, time-invariant equations can be used for the component models, which simplifies the analysis procedure immensely. At most airports under normal circumstances, this assumption would seem to be valid, but during times when the demand is near or over capacity (saturation) the steady-state assumption is questionable. Also, the airport landside is a flexible, dynamic system in which the capacities and service rates are continually changeable. The service capacity of a ticket counter, for example, depends largely on the number of agents serving the passengers. This number can and does change considerably as the passenger demand varies. Because the numbers can change frequently, the steady-state assumption is not always ideal. Nevertheless, the steady-state assumption is necessary for workable models, and is generally realistic.

The second major assumption used in the analysis is that the passenger (and roadway vehicle) arrival rates can be accurately described by the Poisson process.* From the literature surveyed it seems that this is a generally accepted assumption for enplaning passengers. For deplaning passengers, the aircraft arrivals may be modeled as Poisson, but certainly the arrival of passengers within each aircraft is not. There are two comments to be made regarding this phenomenon. First, the equations can be written in terms of Poisson batch arrivals. For this case, each arrival (i.e., aircraft) is Poisson and consists of a batch or group of elements (i.e., passengers). Second, it can be argued that although the exit of passengers from the aircraft is not Poisson, passenger arrivals at the end of the concourse may be Poisson. This is because passengers mix with others from different flights, the walking speed of each passenger varies considerably (thus the concourse spreads them out randomly), time may be spent at restrooms, on telephones, at concessions, or with greeters, which tend to "randomize" the passenger arrivals, etc. Nevertheless, it is assumed in the analysis that all arrivals are Poisson.

A third major assumption is that the passenger arrival rate at one service component (say, security) is not dependent upon the service or congestion at any other component (say, curbside). More specifically, the probability distribution of the

*Heuristically, this distribution is appropriate when it is as likely that a random event occurs (like the arrival of a passenger) at one time as at any other time; also that the occurrence of an event has no effect on whether or not another occurs. More details of random processes and queuing systems are presented in Section 3.

arrivals is unchanged although the demand level may vary. This is partially a consequence of the first two assumptions of *steady state* conditions and Poisson arrival, but mainly this assumption is based upon the wide variation in passenger characteristics. As noted above, the distance between service elements, varying walking speeds, time spent at concessions, telephones, restrooms and with visitors, tends to spread the distribution of passengers. Thus, although severe delay (or lack thereof) at a service facility may alter the arrival patterns at a subsequent facility, this dependence is not explicitly included in the models.

Other assumptions have been made in the development of the analysis. Many of them are made in deriving the component models and are discussed in Section 3. Others were made out of necessity for lack of more accurate information and can be relaxed or replaced whenever desired. For example, the percentage of peak hour passengers using a particular concourse is assumed to be equal to the percentage of passengers who fly the airlines located on that concourse. Thus, if Eastern Air Lines, say, handles 20 percent of the annual passenger traffic at the airport, then it is assumed they also have 20 percent of the peak hour passengers.

2.4 SPECIFIC APPROACH

An examination of Figures 2-2 and 2-3 and Tables 2-1 and 2-2 reveals that the problem of determining landside delays and service times can be very complex. This is especially true for multi-terminal airports where several sets of networks (Figures 2-2 and 2-3) may be necessary to adequately describe the airport. It is critical, therefore, to develop a procedure whereby the landside is analyzed in an orderly, efficient manner. Thus the approach outlined in Table 2-4 has been selected for this airport landside analysis.

The first matter for consideration in the analysis is to specify the airport landside networks of interest. These networks, similar to Figures 2-2 and 2-3, will vary among airports and even among terminals within an airport. Specifically, what is required is the following:

- Identify the passenger service components of interest in the system.
- Indicate the possible paths through the network by linking the components, and the length (distance) of each link.
- Determine the flow splits along each branch point (e.g., the percentage going directly to security versus those using the ticket counter first).
- Determine the values of the major parameters of each component used in the networks (i.e., Tables 2-1 and 2-2).

TABLE 2-4. AIRPORT LANDSIDE ANALYSIS--SPECIFIC APPROACH.

- Specify the landside networks.
- Specify the major control inputs (for example, annual enplanements, fleet mix, modal split).
- Do a flow analysis for the network.
- Determine the per passenger delay at each network element.
- Compute the passenger accumulated times (delay, service, travel) in the network.
- Extrapolate results for annual estimates; print results.

Clearly, a vast amount of data is required even for a single terminal within an airport. Compared to the airside, the landside system of an airport is much more complex, with more permissible variations in passenger routes through the network and more services involved.

The next step in the analysis is to specify the major control inputs to the system. These, as shown in Table 2-3, include the peak (or design) hour passengers, percentage of transfers or connecting passengers, and modal split. These in a sense are the "driving" inputs to the system. Next, a flow analysis is done for the network. Given, for example, that 1000 passengers enter the system during the peak hour and 30 percent proceed directly to ticketing, then the arrival rate at ticketing is 300 in the peak hour. Since the system is assumed to be in a steady-state, the output rate at each unsaturated component equals the input rate. When the arrival rate exceeds the service capacity, the output rate equals the service rate. In this manner a flow analysis for the entire network is performed.

Once the flow analysis is complete and the arrival rates are known, the per passenger delays at each network component can be calculated through the queuing equations for each model (Subsection 3.2). Then the passenger accumulated times, including total travel and service time as well as delay time, can be determined using the network analysis methods described in Subsection 3.3. Finally, the results are extrapolated as indicated in Subsection 3.1 to estimate annual passenger delay times. This approach is very general and flexible enough to be used for a very wide variety of networks and analytic queuing models.

2.5 DATA REQUIREMENTS

The data used as inputs to the models are critical elements in the assessment of airport landside capacity. As indicated above, a large amount of data are required for any airport. Clearly, the accuracy of the output cannot be better than the accuracy of the data inputs. Although comprehensive surveys can be performed at each airport of interest, there are several existing data sources. For this study, it was assumed that the service times for the individual components depend only on the service discipline, the service rendered, and perhaps geometry, but otherwise are airport independent. For example, the processing time at baggage claim or security checkpoint is assumed to be the same for all airports which use similar equipment and procedures. Thus, service times for component models will not in general have to be surveyed at each airport.

Other important parameters appear to be very airport specific. Traffic flows, both vehicle flows at the groundside and people flows in the terminal, depend heavily upon modal splits and passenger types. Furthermore, the variation of a parameter may be very great within any given airport. For example, a traffic survey (Reference 21) at Detroit Metropolitan Airport (DTW) showed a large (but expected) variation in the number of "vehicles per passenger" at different sections of the entrance roadway, as shown in Figure 2-4. This emphasizes the importance of carefully defining the airport parameters both in terms of what is measured and where it is measured.

The Federal Aviation Administration and the Civil Aeronautics Board publish extensive airport data on a regular basis. These include airport activity statistics, passenger demand profiles, and passenger forecasts, as discussed in References 22, 23 and 24, respectively. A recent study (Reference 1) has compiled a comprehensive data book of airport terminal and roadway facilities. Other major data sources are included in the bibliography.

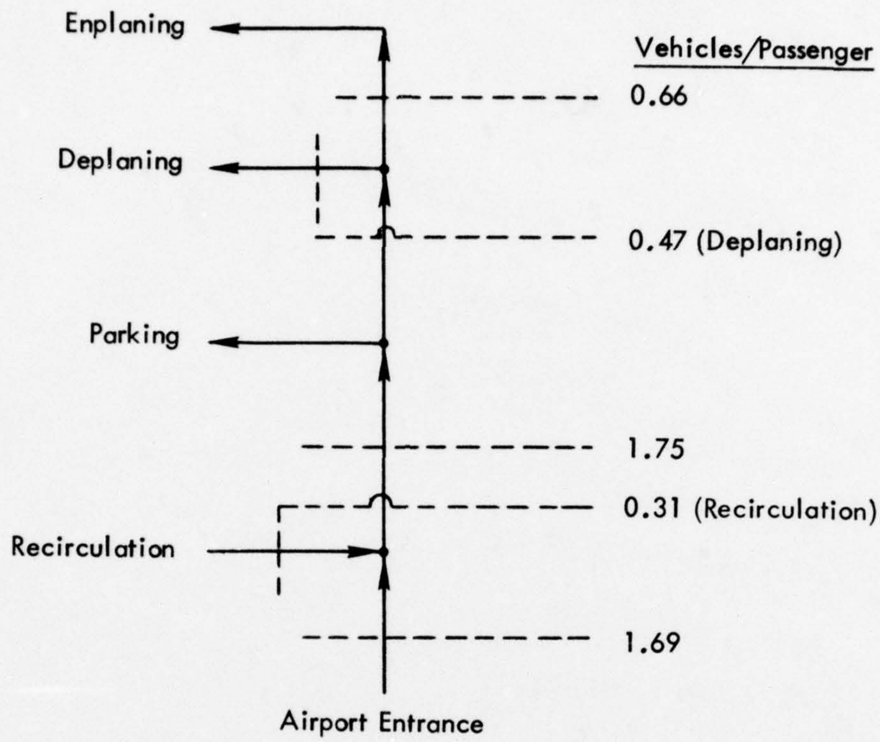

FIGURE 2-4. VARIATION IN VEHICLES PER PASSENGER AT DETROIT METROPOLITAN AIRPORT.

SECTION 3

THEORETICAL DEVELOPMENT

In this section the models and equations used in the landside analysis program are discussed. First an overview of queuing theory is presented followed by a description of the major parameters used to control the landside computer programs. This includes the techniques which are used to estimate annual delay from the design hour calculation and to determine the effects of modal splits and connecting passengers. Next the specific analytic models used to represent the various airport components for the groundside and the terminal are described. Finally the network analysis techniques are derived.

3.1 QUEUING THEORY OVERVIEW

The analytic models used in the landside analysis program are largely based upon the concepts and techniques of classical queuing theory. Volumes have been written on probability theory, random processes, and queuing theory. The intention of this section is to introduce the concepts and define the terminology which is used throughout this report.

Queuing theory involves the mathematical study of "queues" or waiting lines. Decisions regarding the amount of capacity to provide must be made frequently at airports and elsewhere. However, since it is frequently impossible to predict precisely when people will arrive to seek service and how much time will be required to provide that service, these decisions often are difficult ones. Providing too much service would involve excessive costs. Not providing enough service capacity would cause the waiting line to become excessively long. Therefore, the ultimate goal is to achieve an economic balance between the cost of service and the cost associated with waiting for that service. Queuing theory itself does not directly solve this problem. However, it does contribute vital information required for such a decision by predicting various characteristics of the waiting line, such as the average waiting time.

Queuing theory provides a large number of alternative mathematical models for describing a waiting line situation. Mathematical results predicting some of the characteristics of the waiting line often are available for these models. The basic process assumed by the queuing models used in this analysis is the following. Units requiring service arrive over time and are referred to as calling units. These units enter the queuing system and join a queue. At certain points in time, a member of the queue

is selected for service by some rule known as the service discipline. The required service is then performed for the unit by the service mechanism, after which the unit leaves the queuing system. This process is depicted below in Figure 3-1.

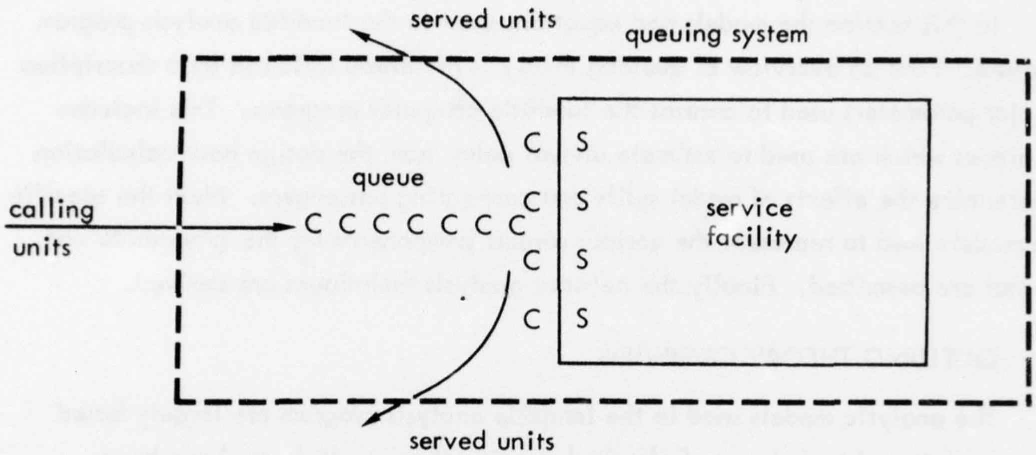

FIGURE 3-1. AN ELEMENTARY QUEUING SYSTEM.

For the airport landside system the calling units are vehicles and passengers. The queues are the lines which form at the various service facilities such as curbs and ticket counters. The service discipline unless noted otherwise is always a "first come-first served" discipline. The service mechanism consists of one or more service facilities, each of which contains one or more "parallel service channels" (servers). If there is more than one service facility, the calling unit may receive service from a sequence of these ("service channels in series"). At a given facility, the unit enters one of the parallel service channels and is completely serviced by that server. A queuing model must specify the arrangement of the facilities and the number of servers (parallel channels) at each one.

The time elapsed from the commencement of service to its completion for a unit at a service facility is referred to as the service time. A queuing model must specify the probability distribution of service times for each server. Also, the probability distribution which describes the rate of arrival of the calling units must be specified.

Unless otherwise noted, the following standard terminology and notation is used in this report:

- k = number of servers (parallel service channels) in the queuing system;
- λ = mean arrival rate (expected number of arrivals per unit time) of new calling units;
- μ = mean service rate (expected number of units completing service per unit time).

With these definitions, $1/\lambda$ and $1/\mu$ are the expected time between arrivals and the expected service time, respectively. Also, $\rho = \lambda/\mu$ is the utilization factor for the service facility, i.e., the expected fraction of time the servers are busy.

The most often used probability distribution functions in queuing theory are the Poisson distribution and the exponential distribution. Another, the Erlang distribution, is also very common but is not used in this study.

A random variable X is said to have a Poisson distribution if its probability distribution can be written as

$$P_x(k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

where λ is a positive constant and k is any non-negative integer. In operations research, the Poisson distribution is often used. Heuristically speaking, this distribution is appropriate in many situations where an "event" occurs over a period of time, like the arrival of a customer; when it is as likely that this "event" will occur in one interval as in any other; also the occurrence of an event has no effect on whether or not another occurs. Then the number of customer arrivals in a fixed time is often assumed to have a Poisson distribution.

A continuous random variable, x, whose probability distribution is given by

$$f_x(y) = \begin{cases} \frac{1}{\mu} e^{-y/\mu}, & \text{for } y \geq 0 \\ 0, & \text{for } y < 0 \end{cases}$$

is known as an exponentially distributed random variable. The exponential distribution is a function of the single parameter μ, where μ is any positive constant. The exponential density function is shown in Figure 3-2.

One of the aspects of choosing the proper queuing model for a given system involves selecting the appropriate probability distribution for the pattern of arrivals and for the service times. If the queuing system is already in operation in some form, statistical theory may be used to help make these decisions. One would need to collect statistical data over time regarding the number of arrivals within time intervals of fixed size (or the time between arrivals) and the service times. Assuming that the mean arrival rate and the mean service time do not change while the data are collected (which may be tested statistically), the arrival and service time distributions could be estimated in a straightforward manner.

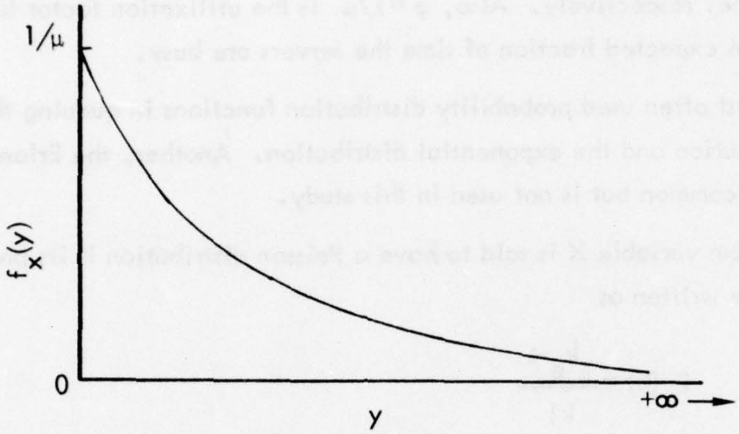

FIGURE 3-2. DENSITY FUNCTION OF THE EXPONENTIAL.

If the arrival of calling units occurs completely at random (at some fixed mean rate), where future arrivals are independent of the pattern of past arrivals, then the input is a Poisson process. It is reasonable to say that many actual queuing systems have a Poisson-like input. Even when an attempt is made to schedule the arrivals to maintain a constant arrival rate, it is frequently observed that unavoidable deviations from the schedule result in the input still being approximately Poisson.

On the other hand, actual queuing systems may often have a service-time distribution other than exponential. In fact, the exponential distribution has two properties which make it inappropriate for many service situations. One of these properties is that the probability density function is strictly decreasing (as shown in Figure 3-2). Thus, if a random variable has an exponential distribution, the maximum probability is at zero; it is not only possible but relatively likely that the random variable will take on a value near zero. Whether this is reasonable for the service-time distribution depends on the nature of the service involved.

The second property of the exponential distribution that deserves special attention is its "lack of memory." In particular, if the random variable is the time a process continues before a service completion, then the process essentially "forgets" how long it has been going. Therefore, an exponential service-time distribution implies that the probability distribution of the time remaining until service is completed is always the same, regardless of how long the calling unit has already been in service.

This may not be realistic in a situation where the same fixed sequence of service operations is performed for each calling unit. In this case, if considerable service time has elapsed, then it is likely that the initial service operations are already completed so that the conditional expected service time for the remaining service operations is less than $1/\mu$.

Since there are three major parameters which describe a queuing system (arrival process, service process, and number of parallel servers) a convenient notation has been developed. This notation refers to a queuing system with three letters such as M/G/k, where the first letter, in this case M, refers to the arrival process, the second, G, the service process, and the third, k, the number of parallel servers. Furthermore, the letter M is conventionally used to refer to either the Poisson or exponential process and G is used to refer to any non-standard or general process. This notation is used throughout this report in the above manner to describe many queuing system models.

3.2 AIRPORT CONTROL PARAMETERS

The number of peak hour enplaning and deplaning passengers is the major input to the landside analytic program. Actually any design hour demand, regardless of whether it is peak hour, can be used to exercise the programs. From the hourly demand rate and the network specifications, all of the delays, travel times and other outputs are calculated.

The hourly passenger demand is usually specified as the total of enplaning and deplaning passengers. In the program, the enplaning and deplaning demands are separately required. Typically the peak total demand does not coincide with either the peak enplaning or the peak deplaning demand. Consider Figure 3-3 which is taken from Reference 23. There the enplaning and deplaning peaks do not coincide; the total peak hour passengers (not shown in Figure 3-3) would have a distribution other than either the enplaning or deplaning charts. An examination of figures in Reference 23 seems to indicate that the enplaning and deplaning peaks are each approximately two-thirds to three-fourths of the total peak. When the separate enplaning and deplaning passenger flows are required, the landside analysis program assumes the ratio is three-fourths of the total peak demand. Any other, preferred ratio can be incorporated into the program.

Many other parameters can be specified to exercise the program; the implementation of these is discussed in this section. Perhaps the most commonly available parameter is the number of annual passenger enplanements at the airport. A method has been developed to estimate the peak hour passengers from the annual enplanements and the airport activity descriptors.

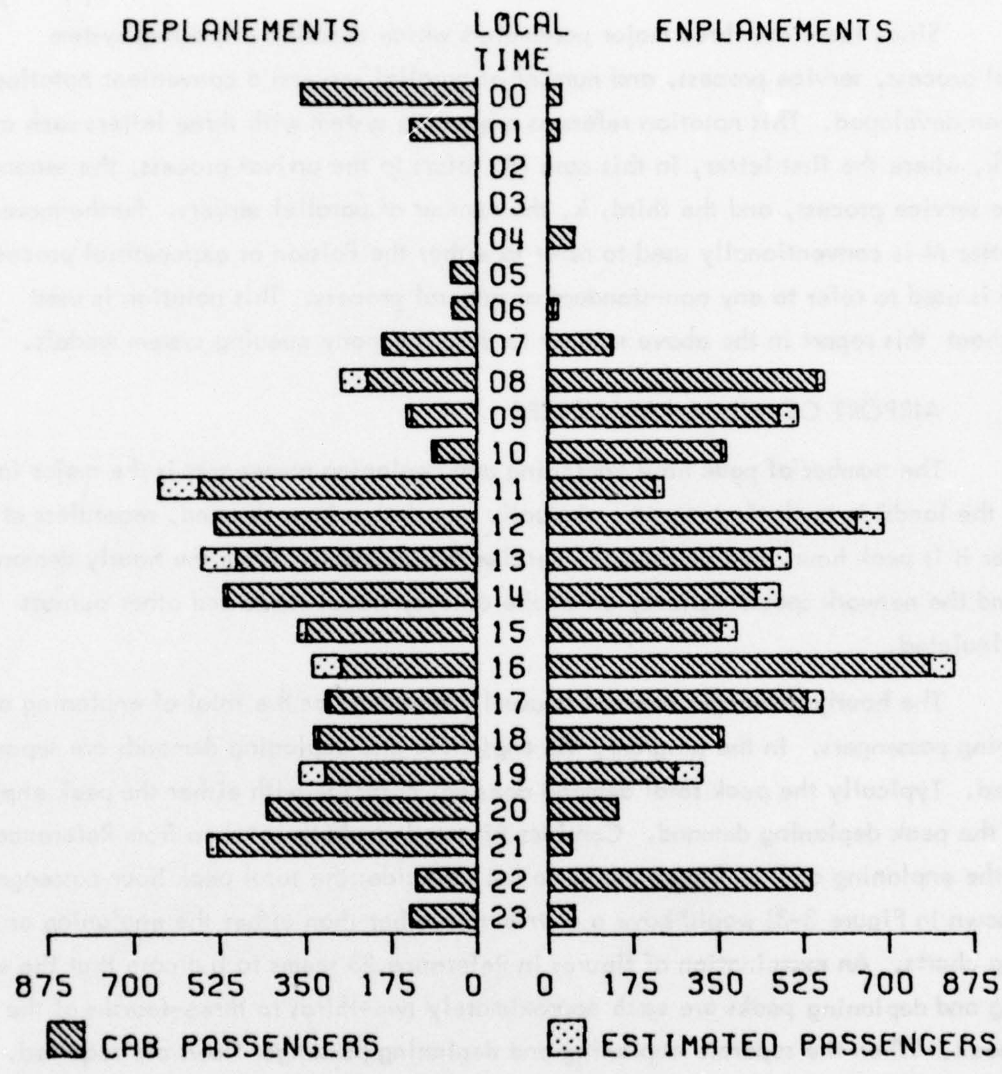

FIGURE 3-3. SCHEDULED PASSENGERS BY HOUR, TAMPA, FLORIDA, FRIDAY, MAY 3, 1974 (Reference 23).

An item of great interest at major commercial airports is the profile of aircraft demand over the 24 hours of a typical day at these airports. A "demand profile" is an hour-by-hour count of the number of operations (landings and takeoffs) scheduled to take place at the airport. *The two main descriptors of demand profiles are:* 1) the number of daily peaks in demand, and 2) the peak hour operations as a percentage of total daily operations. This classification scheme has been developed in Reference 20.

Four separate classes can be identified with respect to the number of daily peaks* (descriptor 1):

a. Single peak demand profiles: these profiles exhibit a single, distinct, more severe and rather prolonged peak period (usually lasting five or six hours). Such a peaking pattern may be due to special circumstances, most often heavy international traffic (e.g., JFK Airport in New York), or geographical location, or heavy pleasure traffic (e.g., Miami Airport).

b. Double peak demand profiles: these profiles exhibit the classical "textbook" pattern of demand with two quite similar peak demand periods, one associated with the morning peak period and the other with that of the evening.

c. No peak demand profiles: in these cases the number of operations remains practically constant throughout most of the normal activity hours. *The uniformity of demand in these cases is often largely due* to capacity problems that force rationing of runway slots ("quota").

d. Multi-peak demand profiles: in a few instances, the demand profile does not fall into any of the categories (a) through (c) above, but exhibits several (three or more) wide fluctuations in the course of a day. This is due to local factors (e.g., Atlanta is the airport where two major airlines base their operations and the major passenger transfer point for these two airlines), or to the lack of any appreciable number of scheduled flights (in which case the distribution of the small number of flights during the day can take odd shapes).

The second descriptor of demand profiles, i.e., the peak hour operations as a percentage of total daily operations, is a rough indicator of the sharpness of the "peaks and valleys" in the demand profile. Typically, this percentage ranges from 12 percent (for airports where peak hour flight frequencies are much higher than in the off-peak hours) to 7 percent (for airports with no peak demand profiles).

*A "peak hour" is a relative, not an absolute term. An airport may have several busy hours, each of which may be referred to as a "peak hour." The handling of a situation *with many peak hours is discussed in this section, (see especially Equation (3-6)).*

The demand profile descriptions of major air carrier airports presented in Table 3-1 are based on the demand profiles shown in the FAA publications (see References 23 and 25) issued by the Aviation Forecast Division at six-month intervals. The particular profiles reviewed were from the report issued in March 1974 and referred to operations on November 2, 1973. Inspection of two subsequent reports showed few differences with these earlier profiles. The November 1973 data were, in any event, preferred as more reliable because they were taken just before the "energy crisis." They are therefore free of the transient effects that initial airline reactions to fuel shortages or price increases may have caused to demand profiles measured later (during 1974).

The standard definition of the design hour or peak hour passengers, PH, is the number of passengers enplaning during the peak hour of the average day of the peak month (Reference 6). The number of peak hour enplanements is estimated from the annual enplanements, AE, and the airport activity descriptors as follows:

$$PH = D2 \cdot AE/(7)(30) \tag{3-1}$$

where D2 refers to the second of the airport activity descriptors; namely, the percentage of the day's operations occurring in the peak hour.

Equation (3-1) implies that the average "peak" month has 30 days and about 14 percent (1/7) of the year's activity. In the absence of other data, this seems to be a reasonable approximation. Equation (3-1) has been developed by ASI and checked by comparing the results with actual numbers from airport master plans and yields acceptable results. Note, however, that the peak hour figure can always be input directly into the computer on an airport specific basis. The above formulation is simply the default used when the operator chooses not to specify the peak hour passengers. This is input not as a percentage figure but as: 1) either the peak hour passenger figure alone, or 2) as both peak hour and annual passenger figures.

The aircraft fleet mix, FM, has a significant influence on the airport activity. As used here the fleet mix is defined as the percentage of wide-bodied passenger aircraft using the airport during the peak hour. Although the quantitative description of the effects of wide bodies on demand profiles is extremely difficult unless an arrival and departure schedule is also specified, a crude approximation can be made. First, the assumption is made that varying the percentage of wide bodies (i.e., fleet mix) does not in itself change the level of annual enplanements. Thus for a given number of enplanements, it is assumed that an increase in the number of wide bodies would tend to

TABLE 3-1. AIRSIDE DEMAND PROFILE DESCRIPTORS.

Air Carrier Airports	Peak Description (descriptor 1)	Peak Hour Operations, Percent (descriptor 2)	Remarks
1. Atlanta, GA			
ATL	Multi	7.0	Very unusual profile with large fluctuations
2. Birmingham, AL			
BHM	Multi	10.1	Few commercial operations
3. Boston, MA			
BOS	Double	7.3	
4. Chicago, IL			
MDW	Double	12.0	Mostly GA
ORD	None	6.8	
5. Cincinnati, OH			
CVG	Double	9.5	
6. Cleveland, OH			
CLE	Double	10.7	
7. Dallas/Ft. Worth, TX			
DAL	Double	7.4	
8. Detroit, MI			
DTW	Double	7.8	
9. Honolulu, HW			
HNL	Double	9.5	
10. Houston, TX			
IAH	Double	7.6	
11. Indianapolis, IN			
IND	Double	8.5	
12. Kansas City, MO			
MCI	Double	9.2	
13. Las Vegas, NV			
LAS	Single	8.8	
14. Los Angeles, CA			
BUR	Multi	9.1	Mostly GA
LAX	Single	7.4	
ONT	Double	11.6	Mostly GA
SNA	Multi	10.6	Mostly GA
15. Miami/Ft. Lauderdale, FL			
FLL	Multi	9.3	
MIA	Single	10.1	

TABLE 3-1. AIRSIDE DEMAND PROFILE DESCRIPTORS (CONTINUED).

Air Carrier Airports	Peak Description (descriptor 1)	Peak Hour Operations, Percent (descriptor 2)	Remarks
16. Minneapolis/St. Paul, MN			
MSP	Single	8.2	
17. New Orleans, LA			
MSY	Double	10.9	
18. New York/Newark, NY/NJ			
EWR	Double	9.0	
JFK	Single	7.7	
LGA	None	7.7	
19. Philadelphia, PA			
PHL	Double	7.2	
20. Phoenix, AZ			
PHX	Double	7.9	
21. Pittsburgh, PA			
PIT	Double	8.2	
22. Portland, OR			
PDX	Single	7.8	
23. San Antonio, TX			
SAT	None	8.3	Few commercial operations
24. San Diego, CA			
SAN	Double	8.2	
25. San Francisco/Oakland, CA			
OAK	Multi	11.0	Mostly GA
SJC	Multi	12.3	Mostly GA
SFO	Double	7.4	
26. Seattle/Tacoma, WA			
SEA	Double	7.9	
27. St. Louis, MO			
STL	Double	7.6	
28. Washington/Baltimore, DC/MD			
BAL	Double	10.2	
DCA	None	6.8	
IAD	Double	10.0	

increase the number of passengers in the peak hour. An examination of the airport activity profiles seems to indicate that there is a correlation between percentage of wide-bodied aircraft and percentage of passengers arriving in the peak hour. Many other factors appear to influence this relationship, including the number of peaks in the day, and a complete description is beyond the scope of this study. For the landside program the following relationship is assumed to calculate D2 only when D2 is not otherwise available or to predict a change in D2 from a change in the fleet mix:

$$D2 = (FM)(0.15) + (0.07) \tag{3-2}$$

Thus, for a fleet mix of wide bodies between 0 and 33 percent (the current maximum range), the percentage of passengers in the peak hour will vary between 7 and 12 percent (the current maximum range). Thus, varying the fleet mix will vary the hourly demand through Equations (3-1) and (3-2).

The hourly passenger demand can also be estimated from the airside demand profile. Here the fleet mix, FM, average aircraft load factor, LF, and peak hour aircraft operations, OPS, are combined to estimate the passenger hourly demand, PH, as follows:

$$PH = OPS \cdot (250 \cdot FM + 100(1 - FM) LF \tag{3-3}$$

Equation (3-3) assumes that a wide-bodied aircraft has an average of 250 passenger seats and the average seating for all other aircraft is 100 passengers. Thus, multiplying the percentage wide bodies, FM, by 250 and the percentage non-wide bodies by 100, and this sum by the average load factor, LF, results in an estimate of the number of passengers aboard a typical aircraft at the airport. Multiplying this by the number of peak hour aircraft operations results in an estimate of the peak hour passengers. Although simple, this technique yields estimates which are quite accurate.

The number of peak hour passengers input to the programs is the total number of peak hour passengers, enplaning and deplaning. Thus, the connecting passengers are already accounted for inside the terminal. For this study it is assumed that all connecting passengers remain inside the terminal complex (i.e., they do not rent cars or otherwise use the roadway). Then the major effect of connecting passengers is their effect on the roadway system. For example, if an airport has no connecting passengers and a peak hour level of 5000 enplaning passengers, then all 5000 enplaning passengers arrive via the roadway. For the same level of activity a 50 percent connecting passenger fraction implies that only 2500 arrive from the roadway. Hence, the roadway demand is 2500 passengers/hour and the terminal demand is 5000 passengers/hour. Thus

$$\text{(Roadway Passenger Demand)} = \frac{\text{(100 Percent Connecting)(PH)}}{100} \quad (3\text{-}4)$$

$$\text{(Terminal Passenger Demand)} = \text{PH} \quad (3\text{-}5)$$

The effect on groundside (roadway) congestion of the passenger modal split is quite dramatic. The techniques for handling this problem are discussed in Subsection 3.3.3.

Another problem encountered in the study is to estimate the annual delays from the peak hour delays (and similarly for service times, etc.). Again the airport activity profile is the key piece of information required. It is assumed that the delays occur only during the peak hours. Thus, if the profile of operations is double peak and 7.2 percent, for example, then the daily delay is twice the peak hour delay. The annual cumulative delay, AD, is estimated in a manner similar to that in which the peak hour demand is estimated from the annual enplanements (Equation 3-1). Thus

$$\text{AD} = (7)(30)(\text{HD})(\text{D1}) \quad (3\text{-}6)$$

where HD = Total delay in peak hour (program output)

D1 = Number of peak hours in the day

The passenger cumulative travel time, AT, and service time, AS, are assumed to be independent of the delay (and the peak hour) and are the same for all passengers. Thus

$$\text{AT} = (\text{AE})(\text{TVL}) \quad (3\text{-}7)$$

$$\text{AS} = (\text{AE})(\text{SVC}) \quad (3\text{-}8)$$

where AE is the level of arrival enplanements and the following are program outputs:

TVL = per passenger average travel time (i.e., time needed to walk to/from the gate, etc.) in system

SVC = per passenger average service time in system

The total time, ATT, spent by passengers in the airport landside during one year is then

$$\text{ATT} = \text{AD} + \text{AT} + \text{AS} \quad (3\text{-}9)$$

3.3 COMPONENT MODELS

A description of the analytic models used in the analysis is presented here. First a general discussion of queuing model selection is presented which includes the M/M/k and M/G/k models often used in the analysis. This is followed by a description of the terminal component models (characterized by passenger and baggage flow) and groundside component models (characterized by vehicle flow).

Unless otherwise specified by the operator of this program, a model used for one component in the system is used for that same component throughout the airport, though the numerical parameters within each model may change. This insures consistency within the program regarding the relative sizes of the delays, service times, etc.

3.3.1 Queuing Model Selections

The M/M/k and M/G/k Models

After an exhaustive search through previous related study efforts, and data-surveying efforts at various airports, it was decided that two major types of models could be accurately used for the majority of the landside components: an M/M/k and an M/G/k queuing model. (Many variations and refinements have been made as appropriate and are described subsequently.) As discussed earlier, the notation indicates that the queuing system has an arrival process which is M (i.e., Poisson), a service process which is M or G (General), and k independent service channels. The solution of the M/M/k problem is well known, and has been programmed for use in this study. The M/G/k problem, which has only recently been approximately solved analytically, is also a key part of the analysis.

The M/M/k routine computes the average per passenger delay (and other parameters as noted below) for a queuing system where: 1) the arrivals are random and characterized by a Poisson process, 2) the service rate is random and characterized as exponential, and 3) there are k independent parallel service channels. The equations for this process are well known and can be found, for example, in Reference 26:

Define

λ = arrival rate (users/minute)

μ = service rate (users/minute)

k = number of parallel servers

L = expected line length (including those in service)

W = expected waiting time (including service time)

L_q = expected queue length

W_q = expected waiting time (excluding service)

and an internal variable

P_n = probability that system is in state n (n = number in line plus number in service). Also, therefore, P_0 is the probability that there is no queue (n = 0).

Then the steady-state system equations are given by

$$P_0 = \left\{ \sum_{n=0}^{k-1} \frac{(\lambda/\mu)^n}{n!} + \frac{(\lambda/\mu)^k}{k!} (1-\rho)^{-1} \right\}^{-1} \tag{3-10}$$

$$L_q = P_0 (\lambda/\mu)^k \rho/k!(1-\rho)^2 \tag{3-11}$$

$$L = L_q + \lambda/\mu \tag{3-12}$$

$$W_q = L_q/\lambda \tag{3-13}$$

$$W = W_q + 1/\mu \tag{3-14}$$

where $\rho = \lambda/\mu k$ (3-15)

is the utilization factor discussed earlier and is the expected fraction of time the servers are busy. The above are subject to the following conditions:

$$\lambda < \mu k \tag{3-16}$$

$$k \geq 1 \tag{3-17}$$

For the landside analysis program the key item of interest is the expected waiting time, W_q, given by Equation (3-14). The inputs are the expected mean arrival rate, service rate, and service channels (λ, μ, and k, respectively).

The M/G/k routine computes the approximate average per passenger delay (and other parameters as noted below) for a queuing system where 1) the arrivals are random and characterized by a Poisson process, 2) the service rate is a completely general random variable characterized by its mean and its variance, and 3) there are k independent parallel service channels. Closed form, approximate solutions for some quantities of interest related to this queuing system have only recently been obtained in a paper by Nozacki and Ross (Reference 27).

The parameters are the same as for the M/M/k routine noted above except

s = average service time

s_2 = second moment of service time.

Then, for

$$\lambda < \mu k = k/s \tag{3-18}$$

$$k \geq 1 \tag{3-19}$$

the expected waiting time is approximately

$$W_q = (\lambda^k s_2 s^{k-1}) / 2(k-1)!(k-\lambda s)^2 \left[\sum_{n=0}^{k-1} \frac{(\lambda s)^n}{n!} + \frac{(\lambda s)^k}{(k-1)!(k-\lambda s)} \right] \tag{3-20}$$

and

$$L_q = W_q \lambda \tag{3-21}$$

$$W = W_q + s \tag{3-22}$$

$$L = \lambda W \tag{3-23}$$

Note that the expression for W_q, Equation (3-20), reduces to the same expression for an M/M/k system when the service time is exponential, i.e., when $2s^2 = s_2$.

Saturation

The equations used in the subroutines for determining the average per passenger delay assume that steady state conditions exist. There are two major problems which arise from this assumption. First, and most importantly, the inputs to the models are the hourly demands. This hourly demand may not be a long enough time to fully reach steady state throughout the airport. The arrival rates may, in fact, fluctuate within the hour. However, most of the delay incurred at an airport occurs during the peak hour and it is appropriate to concentrate the study efforts on this time.

The second difficulty arises when the arrival rate exceeds the total service rate at a facility (saturation occurs). This situation is very common at certain components during the peak hour (roadway and security, for example) and is tolerated because these excess demand conditions are usually transient. However, steady state queuing equations by definition do not consider transient conditions.

One common deterministic way to overcome this problem is to estimate the total passenger delay incurred as a result of the excess demand and then find the approximate per passenger delay by dividing by the number of passengers. For example, assume the average arrival rate, λ, at a facility exceeds the total service rate, μk, as shown in Figure 3-4 for a time interval T. Note that only this time interval is examined, and the arrival rate at other times is assumed to be zero. (In practice, the effect of subsequent arrivals can be similarly determined and the total delays approximated through superposition.)

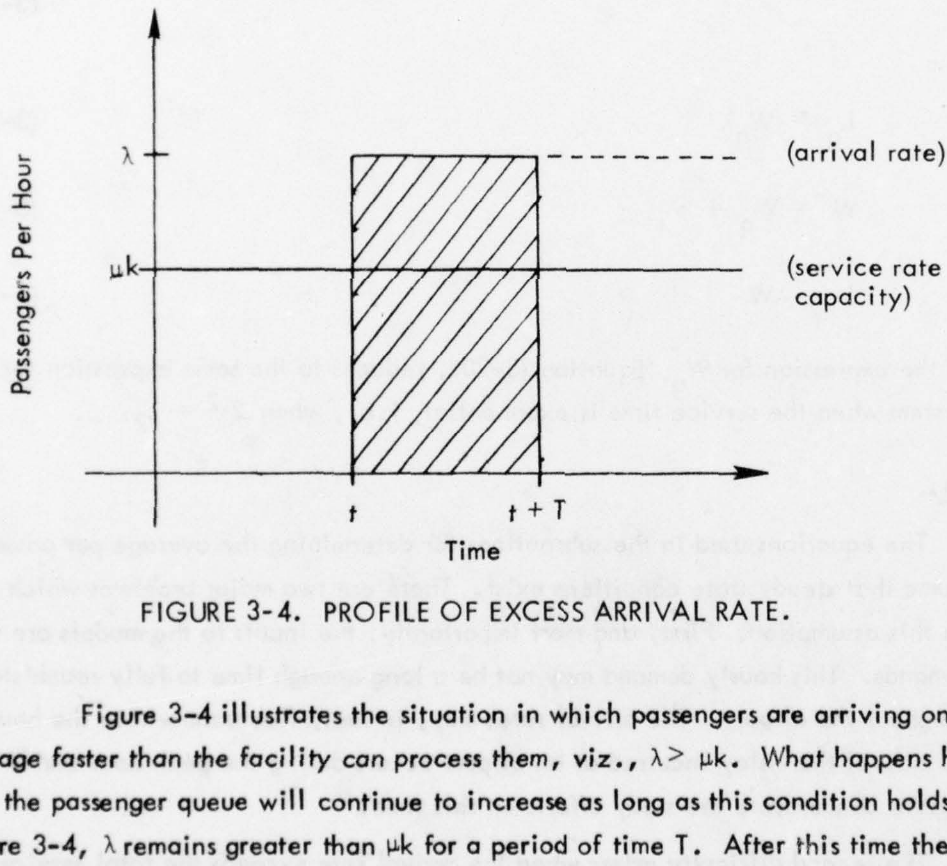

FIGURE 3-4. PROFILE OF EXCESS ARRIVAL RATE.

Figure 3-4 illustrates the situation in which passengers are arriving on the average faster than the facility can process them, viz., $\lambda > \mu k$. What happens here is that the passenger queue will continue to increase as long as this condition holds. In Figure 3-4, λ remains greater than μk for a period of time T. After this time the arrival rate is assumed to be zero and the servers at the facility now "catch up" and handle those passengers still in the queue. The servers will process these passengers at the total service rate of μk.

In Figure 3-5 the excess demand is plotted as a function of time for this situation. Since the total service rate is μk, the excess demand builds up a rate of $(\lambda - \mu k)$.

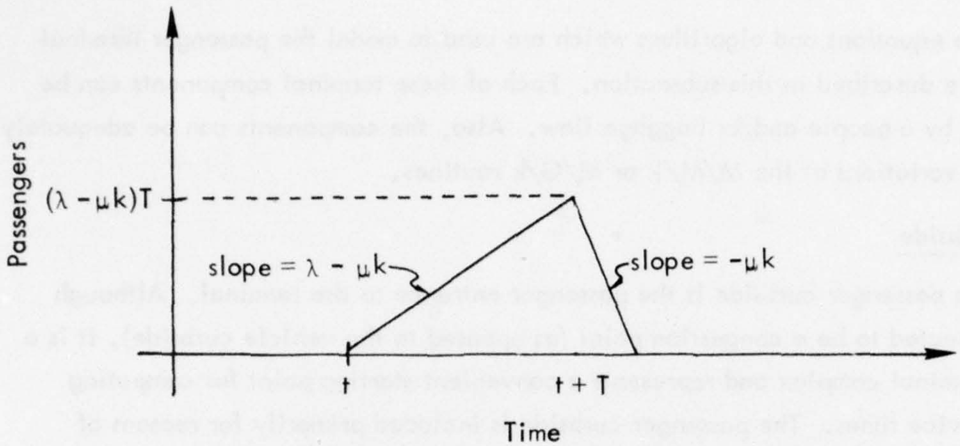

FIGURE 3-5. BUILDUP AND REDUCTION OF QUEUE DUE TO EXCESS DEMAND.

The ordinate indicates the buildup of the queue (in passengers) for the first T time units and the reduction of this queue at a rate μk after the arrivals cease. The area under this curve represents the approximate excess passenger-hours of delay as a result of the excess capacity. Mathematically this can be represented, after some simplification, as

$$\text{(Total Excess Delay)} \approx \frac{\lambda T^2(\lambda - \mu k)}{2\mu k} \tag{3-24}$$

Since during the time T a total of T passengers arrived, the approximate excess per passenger delay is found from Equation (3-24) as simply

$$\text{(Average Excess Per Passenger Delay)} \approx T(\lambda - \mu k)/2\mu k \tag{3-25}$$

Although this is a deterministic approximation of a complex process, the results obtained by using Equation (3-25) are generally quite reasonable.* In fact, this method has been used extensively with only minor modification in many similar studies (for example, Reference 28).

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*Note that this is the extra delay due to the saturation and that the nominal delay due to the queuing (for $\lambda < \mu k$) must be added to this. Also note that the delay is time dependent. That is, it varies linearly with the length of time during which saturation occurs. For the programs used in this study this time is an input variable nominally set at less than one hour.

3.3.2 Terminal Component Models

The equations and algorithms which are used to model the passenger terminal components are described in this subsection. Each of these terminal components can be characterized by a people and/or baggage flow. Also, the components can be adequately modeled with variations of the M/M/k or M/G/k routines.

Passenger Curbside

The passenger curbside is the passenger entrance to the terminal. Although this is not expected to be a congestion point (as opposed to the vehicle curbside), it is a part of the terminal complex and represents a convenient starting point for computing travel and service times. The passenger curbside is included primarily for reasons of model completeness and is modeled as an M/M/k queuing system. The arrival rate is the number of design hour passengers entering the particular terminal zone. The service time is the length of time required to pass from the vehicle curbside into the terminal lobby. The number of "servers" is equal to the number of terminal doorways or entrances. Figure 3-6 illustrates the difference between the passenger curbside and the vehicular curbside used in the groundside modeling.

Ticket Counters

A key terminal service component is the ticket counter. The term ticket counter as used here refers to any of a wide variety of services from a full service counter including baggage check-in and seat assignments, to information-only counters. The ticket counter queuing system has been extensively studied, especially by the airlines (e.g., References 3, 4, 5 and 29). The most commonly used model is the M/M/k model with the service time dependent upon the type of service offered. For example, the service rate for baggage check-in only, would be considerably less than that for international flight ticketing with passport checking. The number of servers, k, is the number of stations available for ticketing (alternately, it can easily be set to represent the number of counters actually in use during the hour considered).

Security Inspection

Observations during the data collection phase of a recent report (Reference 30) and the subsequent analysis of the data, indicate that equipment configuration, conveyor belt speeds, and passenger walking distance through the security areas were important parameters that influenced the processing time. Five different systems were studied including manual baggage search, series and parallel automatic systems. For

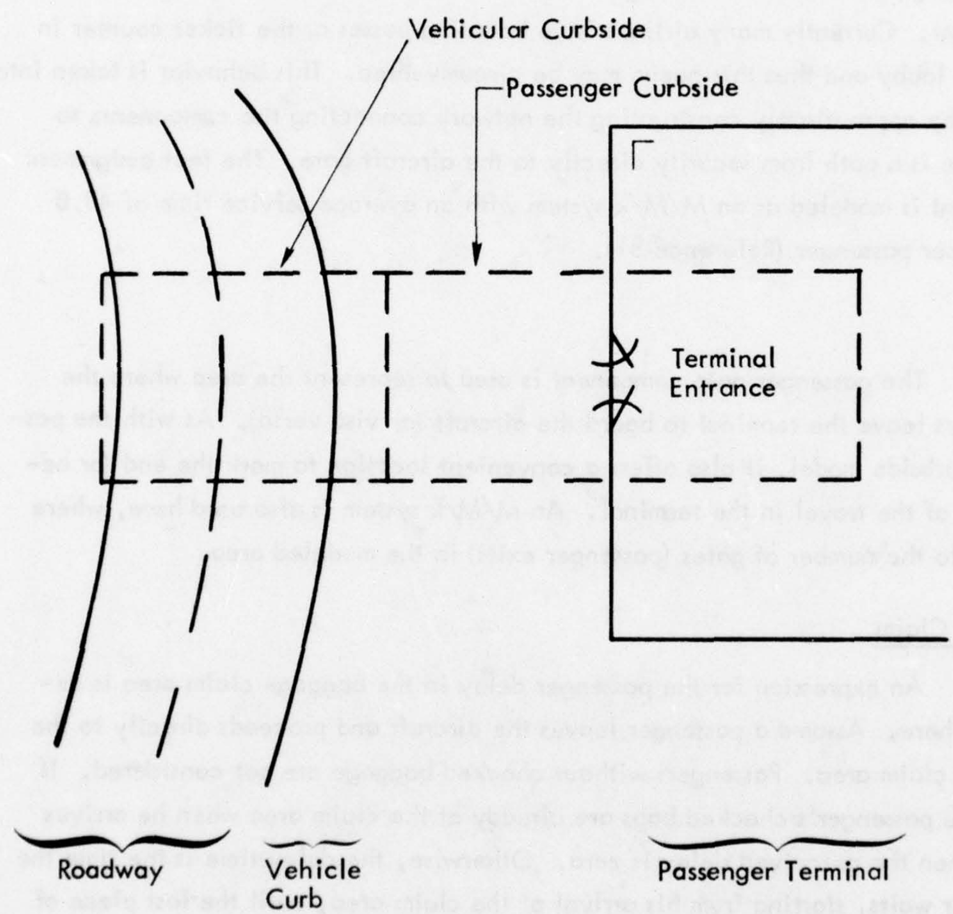

FIGURE 3-6. ILLUSTRATION OF DIFFERENCE BETWEEN VEHICULAR AND PASSENGER CURBSIDE AS DEFINED AND MODELED IN THE LANDSIDE ANALYSIS PROGRAM.

the landside analysis program an M/G/k model is used, where k refers to the number of independent channels or queues at each location. The mean and variance of the service depend upon the system used and, when applicable, are taken from Reference 30.

Seat Assignment

The boarding lounge area is often where passenger tickets are exchanged for boarding passes and a seat assignment; this is defined here as the seat assignment component. Currently many airlines issue boarding passes at the ticket counter in the main lobby and thus this queue may be circumvented. This behavior is taken into account by appropriately constructing the network connecting the components so that there is a path from security directly to the aircraft gate. The seat assignment component is modeled as an M/M/k system with an average service time of 40.0 seconds per passenger (Reference 31).

Gate

The passenger gate component is used to represent the area where the passengers leave the terminal to board the aircraft (or vise versa). As with the passenger curbside model, it also offers a convenient location to mark the end (or beginning) of the travel in the terminal. An M/M/k system is also used here, where k refers to the number of gates (passenger exits) in the modeled area.

Baggage Claim

An expression for the passenger delay in the baggage claim area is developed here. Assume a passenger leaves the aircraft and proceeds directly to the baggage claim area. Passengers without checked baggage are not considered. If all of the passenger's checked bags are already at the claim area when he arrives there, then the perceived delay is zero. Otherwise, the delay time is the time the passenger waits, starting from his arrival at the claim area, until the last piece of checked baggage is retrieved.

Define the following variables:

t_1 = *time it takes the passenger to leave the aircraft and walk to the claim area*

= $N(m_1, \sigma_1)$ [Normal random variable with mean m_1 and variance σ_1^2]

t_2 = time elapsed since leaving the aircraft until the first piece of baggage arrives at the claim area

= $N(m_2, \sigma_2)$

x_i = time since t_2 for the ith piece of baggage for a particular passenger to arrive

= uniformly distributed from t_2 to $t_2 + T$,

where T = length of time from the arrival of the first bag until the last piece of baggage is delivered to the claim area

n = number of bags per passenger

Figure 3-7 illustrates the relationships among these variables and should facilitate their understanding.

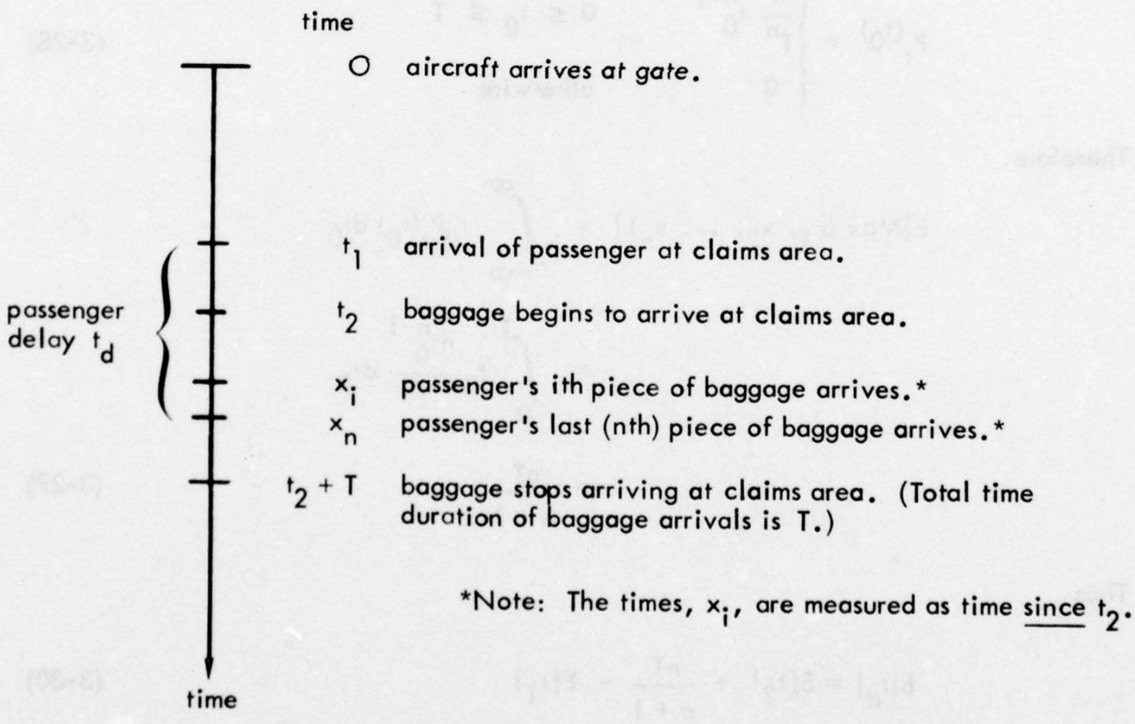

FIGURE 3-7. SEQUENCE OF EVENTS IN BAGGAGE ARRIVAL PROCESS.

The delay, t_d, is defined as

$$t_d = t_2 + \text{Max}\,(x_1, x_2, \ldots x_n) - t_1 \tag{3-26}$$

From the above expression the expected value of the delay is found as

$$E[\,t_d] = E[\,t_2] - E[\,t_1] + E[\,\text{Max}(x_1, x_2, \ldots x_n)] \tag{3-27}$$

The probability density function of the Max $(x_1, \ldots x_n)$ function can be shown to be

$$P_t(t_0) = \begin{cases} \dfrac{n}{T^n}\, t_0^{n-1} & 0 \le t_0 \le T \\ 0 & \text{otherwise} \end{cases} \tag{3-28}$$

Therefore

$$E[\text{Max}\,(x_1, x_2, \ldots x_n)] = \int_{-\infty}^{\infty} t_0 P_t(t_0)\, dt_0$$

$$= \int_0^T t_0 \frac{n t_0^{n-1}}{T}\, dt_0$$

$$= \frac{nT}{n+1} \tag{3-29}$$

Thus

$$E[t_d] = E[t_2] + \frac{nT}{n+1} - E[t_1] \tag{3-30}$$

The preceding expression applies only for values of t_d greater than zero; otherwise, the delay is zero. The above expression is used to determine the expected delay as a function of n, T, $E[t_1]$, and $E[t_2]$.

The final items required are expressions for the expected values for t_1 and t_2 as well as a method to determine T. Since t_1 is the passenger walking time to baggage claim it can be estimated accurately as proportional to the distance from the aircraft gate to the claim area. A nominal walking time of 2 or 3 feet per second can be used as the average walking time. The times t_2 and T are largely dependent upon the baggage handling equipment types and procedures as well as the efficiency of the ground support crews. They are likely to vary among airports and within airports by airline.

Rental Car Area

The rental car area, both check-in and check-out, can be accurately modeled in the same manner as the ticket counters, however, with a different service time. An M/M/k model is used with the mean and variance of the service time taken from the literature (Reference 31).

Federal Inspection Services

The federal inspection services, i.e., passport control and customs are also very similar to ticket counters and an M/G/k model is used. (Note, however, that the assumption of individual Poisson arrivals may be seriously questioned.) A much longer mean service time is usually experienced.

3.3.3 Groundside Modeling

As discussed in Section 2, the groundside of an airport is defined as the part of the airport in which the ground vehicles (buses, autos, etc.) travel. Since the major items of interest are passenger delays and service times, the vehicular delays must be converted into equivalent passenger delays through vehicle-to-passenger ratios. Because the groundside networks are typically much more complex than the terminal networks, additional discussion of the groundside models is required. In this section, the models for the three primary groundside components: parking, roadway, and curbside, are first presented, followed by the calculations pertaining specifically to the groundside network. As with the terminal component models, the groundside models are modular and can be easily replaced. The general network analysis techniques used in both the groundside and terminal areas are presented in Subsection 3.3.4.

Parking Lot

A model has been developed for parking lots with the following basic assumptions about arrival and service patterns:

- Poisson arrivals of cars for parking, i.e., the number of cars arriving in time interval T will be equal to k with probability

$$p(k, T) = \frac{(\lambda T)^k e^{-\lambda T}}{k!} \qquad k = 0, 1, 2, 3, \ldots \qquad (3\text{-}31)$$

- A general distribution for the duration of parking, i.e., a car will be parked at a given parking space for a time period s described by a general probability distribution function $f_s(s_0)$ with $E[s] = 1/\mu$ and $Var(s) = \sigma_s^2$
- An infinite number of servers (i.e., of parking spaces). In other words it is initially assumed that the airport never runs out of car parking spaces.

The parking lot is thus an $M/G/\infty$ type of queuing model. It turns out that some powerful results exist for $M/G/\infty$ queues (see, for example, Reference 32). The most fundamental one of these results is that the probability P(n) that exactly n parking spaces are occupied at a random instant when the system is in steady-state is given by:

$$P(n) = \frac{(\lambda/\mu)^n e^{-\lambda/\mu}}{n!} = \frac{\rho^n e^{-\rho}}{n!} \qquad n = 0, 1, 2, \ldots \qquad (3\text{-}32)$$

where $\rho \stackrel{\Delta}{=} \frac{\lambda}{\mu}$. This result holds independently of the form of $f_s(s_0)$.

The above form for P(n) is just the form for the probability function of a Poisson process. This permits the following inferences about the parking lot model. The average number of parking spaces occupied (in steady-state) is:

$$E[n] = \rho = \frac{\lambda}{\mu} \qquad (3\text{-}33)$$

Assume now that the parking lot has a finite capacity of M parking spaces. Then, if M is a sufficiently large number (as it actually is) the probability, R, that a car will be "rejected" (i.e., that a passenger wishing to park his car will find the lot full) can be very well approximated by using

$$R = \sum_{n=M+1}^{\infty} P_n = \sum_{n=M+1}^{\infty} \frac{\rho^n e^{-\rho}}{n!} \tag{3-34}$$

Thus, for any size lot, Equation (3-34) computes the probability of finding a full lot and, conversely, given a desired probability of rejection (say R = 2%) finds how many parking spaces are needed.

The computation of R, in the above form, is not convenient. Fortunately, since ρ, the average number of parking spaces, is a large number, the normal approximation to the Poisson distribution can be used here. In fact, ρ is so large for any sizable airport and parking lot, that it is even unnecessary to worry about the fact that the number of parking spaces is an integer number, i.e., we can treat the size of the parking lot as a continuous number.

The normal approximation to the Poisson distribution results in

$$R = \sum_{n=M+1}^{\infty} = 1 - \Phi\left(\frac{M-\rho}{\sqrt{\rho}}\right) \tag{3-35}$$

where

$$\Phi(x) = \text{cumulative of a standardized normal variable}$$

$$= \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt \tag{3-36}$$

To understand Equation (3-35) remember that for the Poisson distribution given by Equation (3-32), $E[n] = \rho$ and $\sigma_n^2 = \rho$.

Finally, consider the expected amount of time it will take for a passenger wishing to park his car to find an empty space in the parking lot. Here, unfortunately,

much depends on the specific geometry of the case at hand. Do people park at the first empty space that they find or do they prefer particular locations? Are new arrivals sent directly to a location, e.g., a specific level on a multi-level parking garage where they are likely to find an empty space, or do they search in an "exhaustive way" for a place to park?

For these reasons, it is possible to give only a general upper bound on the approximate time it will take the average "customer" to find an empty space. This bound is:

$$D = t_0 + \alpha E[n] = t_0 + \alpha \rho \tag{3-37}$$

where t_0 is the processing time needed to enter the parking lot (e.g., punching a time stamp, etc.) and α is the time needed to pass by an occupied parking space.

Numerical Examples for Long-Term Parking

To better illustrate the above expressions, it is instructive to examine a numerical example. For the peak days of the year let $\lambda = 3{,}000$ long-term parkers arriving per day. Also let the average time a car is parked at the lot be equal to 1.5 days.

Then, the average number of cars parked is

$$\rho = \lambda \frac{1}{\mu} = (3{,}000)(1.5) = 4{,}500 \tag{3-38}$$

The number of spaces required to assure a probability of only 1 percent that the lot will be full on a peak day is found by solving

$$0.01 = 1 - \Phi\left(\frac{M - 4{,}500}{\sqrt{4{,}500}}\right)$$

or

$$\Phi\left(\frac{M - 4{,}500}{67.08}\right) = 0.99 \tag{3-39}$$

or

$$M - 4,500 = (67.08)(2.33) \quad \text{(from Tables of Normal Areas)} \qquad (3\text{-}40)$$

or

$$\underline{M = 4,667} \quad \text{parking spaces} \qquad (3\text{-}41)$$

This is an interesting result which reports that even though the expected number of cars in the lot is 4,500, if there are only 4,667 total spaces in the lot then there is only a 1 percent probability that a random user will find the lot full.

If a prospective parker travels through the parking lot at, say, 12 mph and if a parking space is 8.5 feet wide, assuming that $t_0 = 1$ minute, an upper bound on the length of time to find a parking space is given by:

$$D_{max} = t_0 + \alpha\rho = 1 \text{ min} + \frac{(8.5)(4,500)}{(12)(5,280 \text{ ft per mile})}$$

$$= 1 \text{ min} + (0.604) \text{ hours} = 37 \text{ minutes} \qquad (3\text{-}42)$$

Clearly, D_{max} is a very loose upper bound in this case since it is very unlikely that the 4,700 or so parking spaces are all in a single giant parking lot. However, a reasonable estimate of the delay incurred in finding a parking space can be found from this expression. Equation (3-37) gives the time spent searching for a space if all occupied spaces were adjacent and encountered before the first empty space was found and used. It seems reasonable that in fact the cars are parked a bit more randomly in the lot. In particular, assume that a fraction p of all spaces are occupied and that the occupied spaces are completely randomly distributed in the parking lot. Then, since the probability of finding a random empty parking space is now 1 − p, the expected delay until an empty space is found is given by

$$D = \alpha \cdot \frac{p}{1 - p} \qquad (3\text{-}43)$$

As a rough check for reasonableness, by considering smaller and smaller parking lots, where the 4,500 average parked cars represented a larger fraction of the total (i.e., as $\rho \rightarrow 1$), then the delays, as expected, increase substantially.

Roadway Delay

The purpose here is to determine an expression for the average delay encountered on the roadway system due to roadway congestion. Here we define the delay as the excess time required to travel a section of road. Thus, when there is no congestion the nominal travel time is simply

$$T_N = D/V_o \tag{3-44}$$

where D is the distance traveled, and V_o is the unimpeded driving speed which is assumed to be the posted speed limit. The actual average speed in traffic is similarly defined as

$$T = D/V_r \tag{3-45}$$

where V_r is the reduced speed due to roadway congestion. Therefore, the delay is found as

$$T_{delay} = T - T_N = (D/V_r) - (D/V_o)$$

$$= \frac{D}{S} (V_o/V_r - 1) \tag{3-46}$$

Before proceeding, it is necessary to determine the reduced speed, V_r. For this, the Highway Capacity Manual (Reference 33) is an excellent source. There, in discussing the relationship between speed, flow, and density, it is noted that the "operating speed" (V_r) is very nearly linearly proportional to average lane volume (cars/hour). This relationship varies with the nominal roadway speed, but the basic pattern is a decrease in speed as the flow rate increases up to a maximum flow rate, then a decrease in flow rate as well as speed until, of course, there is a zero flow rate at zero velocity. As a consequence, there are two stable operating speeds obtainable for a given flow rate less than the maximum as shown in Figure 3-7.

The vehicle flow rate illustrated in Figure 3-7 is the flow rate actually occurring on the roadway and not necessarily the vehicle arrival rate. Thus, for the landside analysis program, the problem is restated such that the reduced (operating) speed is found by first specifying the input arrival rate and then using a relationship such as Figure 3-7 to find the operating speed. Thus, a model is needed which unambiguously relates the arrival rate, λ, to the reduced speed, V_r. Then, the delay is given from Equation (3-46).

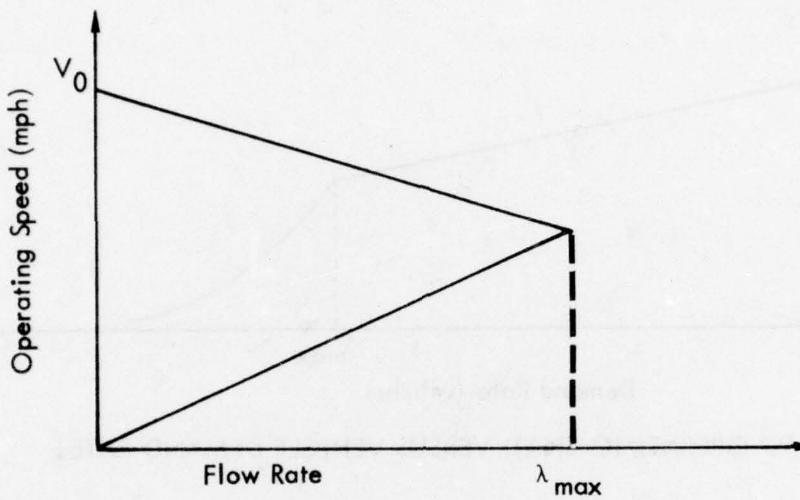

FIGURE 3-8. OPERATING SPEED VERSUS VEHICLE FLOW RATE.

Since the vehicular arrival rate, λ, is determined from the demand at the airport and not from the existing congestion, it is accurate to consider the upper portion of Figure 3-3 as determining the accurate operating speed. For example, if the arrival rate is near zero ($\lambda \approx 0$), then the operating speed is near the speed limit (i.e., V_0) and not near zero. The values of V_o, λ_{max}, and the slope of the curve in Figure 3-8 are determined by existing roadway conditions.

A relationship for the demand rate and operating speed is presented in Figure 3-9. Note that for λ less than λ_{max} Figure 3-9 is identical to the upper part of Figure 3-8 as desired. For a demand rate, λ, greater than λ_{max}, the operating speed drops off sharply to reflect the substantial reduction in operating speed due to the excessive demand. Thus, Equation (3-46) together with Figure 3-9 determines the delay per lane over a roadway section of length, D, where the demand per lane is given by λ.

Vehicular Curbside

The third component of the airport groundside to be modeled is the vehicular curbside. The arrival and distribution of vehicles coupled with the interactions of passengers, baggage and vehicles make this the most complex of systems in the airport.

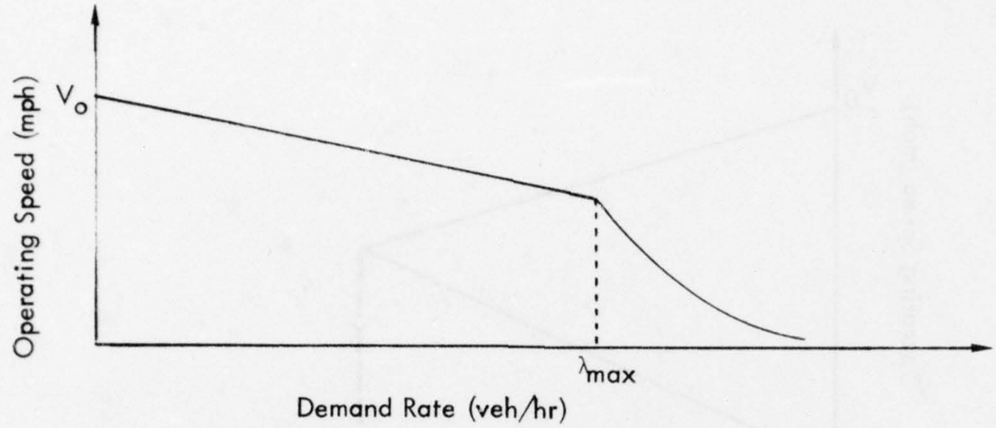

FIGURE 3-9. OPERATING SPEED VERSUS VEHICLE DEMAND RATE.

Several other efforts have been made to model the curbside including Bein (References 34 and 35), and more recently Pararas (Reference 17). Also, several rule-of-thumb guidelines have been prepared, such as the recent Parsons study (Reference 6). The model used in the landside analysis program is basically an expansion of the standard M/M/k queuing model. Although it may not be as sophisticated as other existing models (which are largely untested), it is felt that this model gives a reasonable indication of the delays incurred at the curbside.

The curbside model for the landside analysis program incorporates the number of curbside lanes and the length of curb frontage into the algorithm to estimate the number of usable service (loading/unloading) slots available. Assuming that the average car occupies 25 feet/slot and a bus 50 feet/slot, then the number of parking slots required at the curb is approximately

$$(N) = (L)(f_a/25 + f_b/50) \qquad (3\text{-}47)$$

where N = number of slots available

L = curb length

f_a = fraction of automobiles

f_b = fraction of buses

A recent study (Reference 36) indicates that curb frontage is only about 70 percent effective. That is, out of every ten spaces actually available only seven can be effectively used. This is due to many factors, the primary ones being that vehicles are not spaced as closely as in a parking lot and that they tend to be parked as close to a terminal entrance as possible, regardless of available space farther away from an entrance. Thus, the model in the landside program uses a 70 percent efficienty factor for the first curb lane:

$$N_e = 0.70\ N \tag{3-48}$$

where N_e is the effective number of curb slots. Based upon the results presented in Reference 36, adjacent curb lanes are assumed to be only half as efficient as the first lane,* thus,

$$N_{ei} = (0.50)^{i-1}\ (0.70)\ N \tag{3-49}$$

is the expression used for the number of slots in the ith lane away from the terminal curb. Then the total number of slots available is given by

$$K = \sum_{i = \text{number of lanes}} N_{e_i} \tag{3-50}$$

The service time of a vehicle occupying a curb slot is proportional to the number of bags per passenger. Also, the deplaning curb dwell time is noticeably longer than the enplaning dwell time. From an examination of other studies (e.g., References 21, 32, and 36) the following relationships have been developed for the average enplaning, t_e, and deplaning, t_d, curb times for each piece of baggage.

$$t_e = 80\ \text{sec/bag} \tag{3-51}$$

$$t_d = 120\ \text{sec/bag} \tag{3-52}$$

Thus, the curbside model uses the total curb frontage, vehicle mix, and number of lanes to determine the effective parking slots available through Equation (3-50) and the number of bags per passenger, plus Equations (3-51) and (3-52) to determine the expected average service times. Then the M/M/k subroutine is used to estimate the approximate average passenger delay time.

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*If additional, more accurate data becomes available, this efficiency factor can be easily changed in the program.

Groundside Area Networks

For this study, the entire airport roadway system can be broken into several smaller systems referred to as "terminal-roadway units." As discussed subsequently, the network for each such unit can contain up to eight components, including, for example, parking lot, enplaning curb, main roadway in, and terminal roadway out. Each terminal-roadway unit serves one terminal building which may include more than one terminal zone; large terminals housing several airlines are divided into separate zones to facilitate the network analysis. The resulting airport groundside network is thus much more manageable without sacrificing accuracy. For example, Figure 3-10 shows the roadway network breakdown used in analyzing Boston Logan airport. Four terminal roadway units are formed by combining each circled area with a main roadway in and main roadway out component. Figure 3-10 itself represents the entire groundside system.

Vehicle arrivals into each groundside terminal unit are assumed to be proportional to the amount of passenger traffic handled by the airlines in that terminal. In order to determine the flows between components within the groundside, it is necessary to know the vehicle modal breakdown of the traffic flow. This is also used to compute realistic per passenger delays at each component. For example, only private autos will reach the parking lot, whereas the curbside will be shared by autos, taxis and buses. The per vehicle delays are converted to per passenger delays using values for passenger/vehicle-by-type. The vehicle modal split is computed from the passenger modal split and the passenger per vehicle ratios. First note that (pax = passenger, veh = vehicle):

$$\text{veh/pax} = \frac{\text{Total number vehicles all types}}{\text{Total enplanements}} \tag{3-53}$$

and

$$\text{Total number vehicles all types} = \frac{\text{Pax arriving by auto}}{\text{pax/auto}} + \frac{\text{Pax arriving by taxi}}{\text{pax/taxi}} + \frac{\text{Pax arriving by bus}}{\text{pax/bus}} + \frac{\text{Pax arriving by rail}}{\text{pax/rail}} \tag{3-54}$$

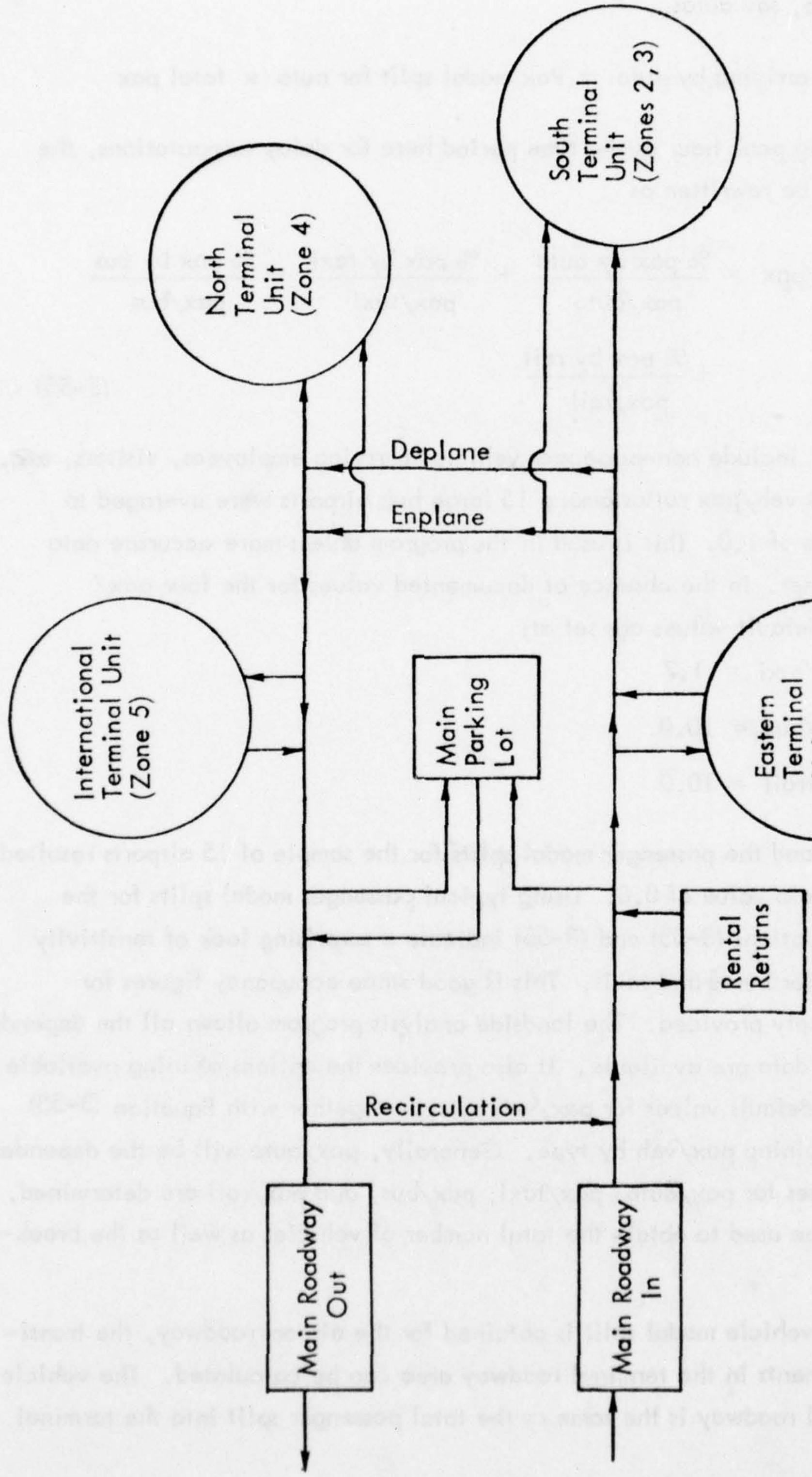

FIGURE 10. TYPICAL ROADWAY NETWORK - BOSTON LOGAN AIRPORT.

For each vehicle type, say autos,

$$\text{Pax arriving by auto} = \text{Pax modal split for auto} \times \text{total pax}$$

Considering peak hour as the time period here for delay computations, the above equations can be rewritten as

$$\text{veh/pax} = \frac{\%\ \text{pax by auto}}{\text{pax/auto}} + \frac{\%\ \text{pax by taxi}}{\text{pax/taxi}} + \frac{\%\ \text{pax by bus}}{\text{pax/bus}} + \frac{\%\ \text{pax by rail}}{\text{pax/rail}} \qquad (3\text{-}55)$$

Note that the "autos" include non-passenger vehicles carrying employees, visitors, etc. Available data on the veh/pax ratios among 15 large hub airports were averaged to yield a veh/pax value of 1.0. This is used in the program unless more accurate data are provided by the user. In the absence of documented values for the four pax/veh-by-type ratios, default values are set at:

pax/taxi = 1.7

pax/bus = 10.0

pax/rail = 10.0

These default values and the passenger modal splits for the sample of 15 airports resulted in a consistent pax/auto value of 0.8. Using typical passenger modal splits for the largest airports in Equations (3-53) and (3-55) indicate a surprising lack of sensitivity to the pax/veh ratio for buses and taxis. This is good since occupancy figures for these vehicles are rarely provided. The landside analysis program allows all the dependent to be input when the data are available. It also provides the options of using available input data and three default values for pax/veh by type together with Equation (3-55) to determine the remaining pax/veh by type. Generally, pax/auto will be the dependent variable. Once values for pax/auto, pax/taxi, pax/bus, and pax/rail are determined, Equation (3-54) can be used to obtain the total number of vehicles as well as the breakdown by type.

Once the vehicle modal split is obtained for the airport roadway, the transitions between components in the terminal roadway area can be calculated. The vehicle split into the terminal roadway is the same as the total passenger split into the terminal

zones served by the terminal-roadway unit. The documented data (Reference 21) on Detroit Metropolitan Airport (DTW) were used for determining splits within the roadway complex, since the roadway survey taken at Detroit is the most complete survey available which is applicable to this study and is believed to be typical of all major airports. The following data were obtained from Detroit on passengers arriving and leaving the terminal curb areas:

Enplanements		Deplanements	
55.0%	from parking lot (autos)	73.2%	to parking lot (autos)
32.8%	from autos (at curb)	14.2%	to autos (at curb)
1.6%	from taxis	3.2%	to taxis
10.6%	from buses, limos	9.4%	to buses, limos

The following assumptions are also used:

- The flow of vehicles entering the terminal roadway complex equals the vehicle flow out.
- 90 percent of autos at deplaning curb arrive there from parking lot; 10 percent come directly from outside the airport.
- 75 percent of autos with enplaning passengers go to parking lot, either directly or via enplaning curb; the remaining 25 percent leave the airport.

The resulting vehicle movements in the groundside terminal-unit are listed in Table 3-2.

TABLE 3-2. MOVEMENT OF ENTERING VEHICLES.

Autos:	80% to parking lot
	19% to enplaning curb
	1% to deplaning curb
	7% to deplaning curb from parking lot
	6.5% to parking lot from enplaning curb
Taxis:	33% to enplaning curb
	67% to deplaning curb
Buses:	50% to enplaning curb
	50% to deplaning curb
Rail:	50% to enplaning curb
	50% to deplaning curb

Note: If separate curbs are not available for enplaning and deplaning vehicles, figures for the one curb are the sum of the enplaning and deplaning figures shown.

An examination of major air carrier airports indicates that the airport groundside network can usually be modeled as a combination of one of two basic configurations: 1) with separate enplaning and deplaning curbs (Figure 3-10), and 2) with a single curb for both enplaning and deplaning passengers (Figure 3-11). The flow splits within each groundside system and the conversion from vehicle delays to passenger delays is accomplished as follows. The notation used and illustrated in Figures 3-11 and 3-12 and Tables 3-3 and 3-4 is given here:

- Vehicle Modal Split $= (v_1, v_2, v_3, v_4) =$ (% auto, % taxi, % bus, % rail)
- Roadway Splits $= \alpha_1, \alpha_2, \ldots$ = fraction of vehicles traveling roadway segment
- Vehicle mix arriving at enplaning curb $= (e_1, e_2, e_3, e_4) =$ (% auto, % taxi, % bus, % rail)

The values for the α_i's into each component are used to derive the vehicle mix for that state. For example, if $\alpha = 0.01v_1 + 0.67v_2 + 0.5v_3 + 0.5v_4$ into the E (enplaning) curb, then the expression for (e_1, e_2, e_3, e_4) is given by $(0.01v_1/\alpha,\ 0.67v_2/\alpha,\ 0.5v_3/\alpha,\ 0.5v_4/\alpha)$ and thus

$$\text{Delay/pax} = \frac{\text{Delay/vehicle}}{\left[\frac{\text{pax}}{\text{auto}}(e_1) + \frac{\text{pax}}{\text{taxi}}(e_2) + \frac{\text{pax}}{\text{bus}}(e_3) + \frac{\text{pax}}{\text{rail}}(e_4)\right]} \qquad (3\text{-}56)$$

Once the per passenger delay has been computed for each groundside component, an expected value of delay for the entire groundside network is obtained as described for the terminal building example in Subsection 3.3.4.

3.4 NETWORK ANALYSIS

As previously discussed in Section 2, the airport landside analysis involves two major areas: (1) component identification and modeling, and 2) network analysis. Examples of the networks of interest have been presented in Figures 2-2 and 2-3, and some of the specific analyses required for the groundside analysis have been discussed in Subsection 3.3. In this section, the techniques used in the network analyses are developed. These methods are very general and are used for both the groundside and terminal networks.

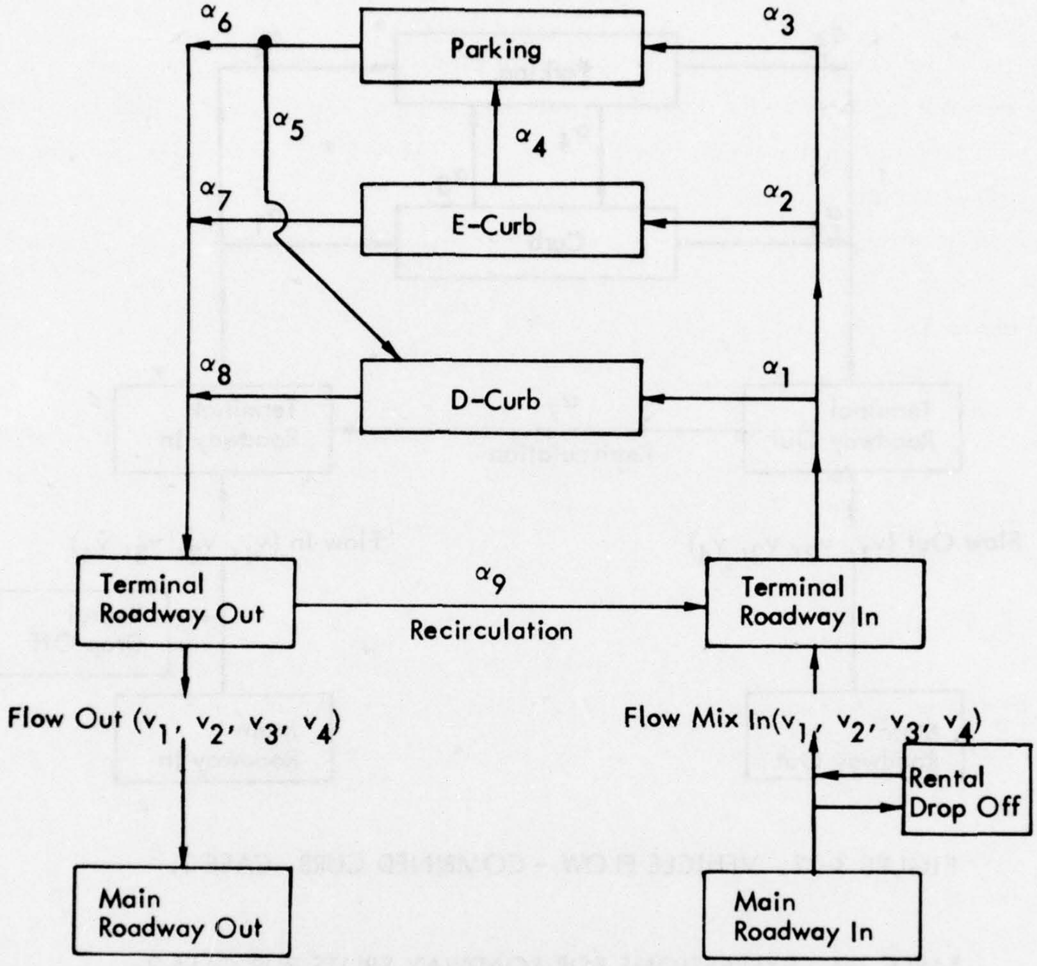

FIGURE 3-11. VEHICLE FLOW - SEPARATE CURBS, CASE 1.

TABLE 3-3. EXPRESSIONS FOR ROADWAY SPLITS FOR CASE 1.

$\alpha_1 = 0.01v_1 + 0.67v_2 + 0.5v_3 + 0.5v_4$	$\alpha_6 = 1 - \alpha_5$
$\alpha_2 = 0.19v_1 + 0.33v_2 + 0.5v_3 + 0.5v_4$	$\alpha_7 = 1 - \alpha_4$
$\alpha_3 = 0.8v_1$	$\alpha_8 = 1.0$
$\alpha_4 = 0.065v_1/\alpha_2$	$\alpha_9 = 0.17$ (ifrecirculation road available)
$\alpha_5 = 0.07v_1/\alpha_3$	

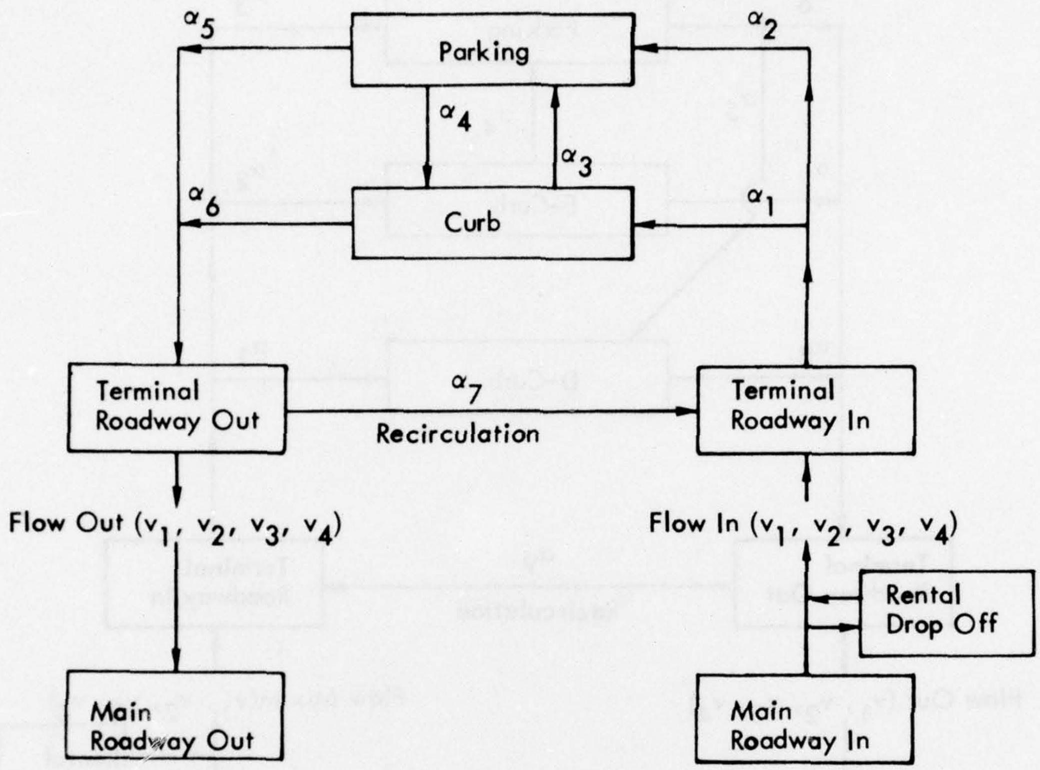

FIGURE 3-12. VEHICLE FLOW - COMBINED CURB, CASE 2.

TABLE 3-4. EXPRESSIONS FOR ROADWAY SPLITS FOR CASE 2.

$$\alpha_1 = 0.2v_1 + v_2 + v_3 + v_4$$

$$\alpha_2 = 0.8v_1$$

$$\alpha_3 = 0.065v_1/\alpha_1$$

$$\alpha_4 = 0.07v_1/\alpha_2$$

$$\alpha_5 = 1 - \alpha_4$$

$$\alpha_6 = 1 - \alpha_3$$

α_7 = 0.17 (if recirculation road available)

The parameters of most interest in the landside analysis program are the average passenger time spent in the system, including delay time. This is not a simple calculation since there are, in general, many possible paths through the system (or network) and different percentages of passengers travel each link in the network. The method of effectively determining all of the different paths and the fraction traveling each one is the subject of the following discussions. First, a simple example of the technique is presented which clearly illustrates the fundamental concepts. This is followed by a more theoretical development of the equations involved.

Network Analysis Example

Following is an example which illustrates the technique used in the network analysis for this study. The example as illustrated in Figure 3-13 is a hypothetical case involving one airline with "regular" and "shuttle" flights. Regular passengers depart from Gate 1 and all use the seat assignment queue; shuttle passengers do not receive seat assignments although they and the regular passengers may use the ticket counter. The problem is to develop an efficient method for computing the average total time per passenger spent in the system. This will be a sum of the average per passenger delay, travel time, and processing time.

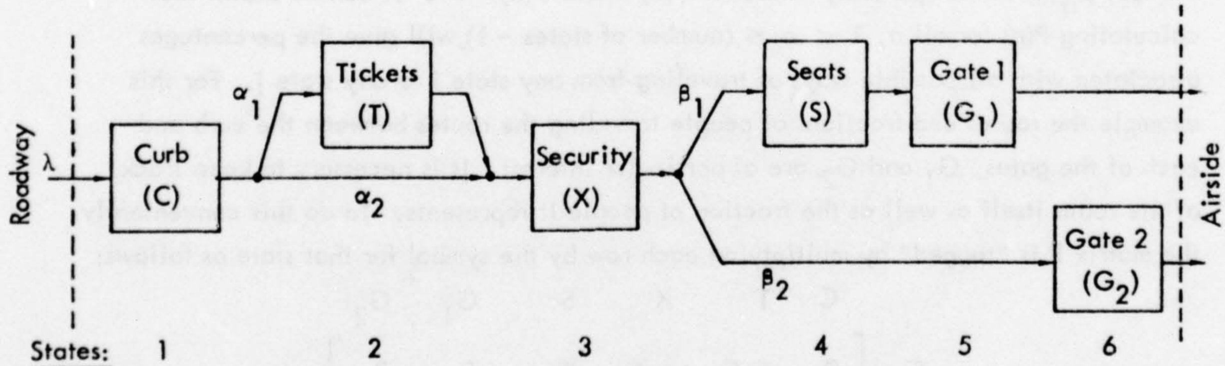

FIGURE 3-13. AIRPORT TERMINAL NETWORK (EXAMPLE 1).

From Figure 3-13 the state probability transition matrix, P, is constructed. Each component in the network is referred to as a state. Each element of the matrix, p_{ij}, is the probability of passengers traveling directly from state i to state j. The transition matrix for Figure 3-13 is shown below.

From \ To	C	T	X	S	G_1	G_2
C	0	α_1	α_2	0	0	0
T	0	0	1	0	0	0
X	0	0	0	β_1	0	β_2
S	0	0	0	0	1	0
G_1	0	0	0	0	0	0
G_2	0	0	0	0	0	0

Transition Matrix P for Figure 3-13.

Note that $0 \le p_{ij} \le 1$ and $\sum_{j=1}^{n} p_{ij} = 1$ for all rows, i, except the final states, G_1 and G_2. Thus, p_{ij} can be equivalently regarded as the fraction of people traveling directly from state i to state j. The fraction of people moving from state i to state j in exactly n steps, $p_{ij}(n)$ is the ijth entry of matrix P(n) where $P(n) = P^n$. It can be shown that calculating P(n) for all n, $1 \le n \le$ (number of states − 1), will give the percentages associated with all possible ways of traveling from any state i to any state j. For this example the routes and fractions of people traveling the routes between the curb and each of the gates, G_1 and G_2, are of particular interest. It is necessary to keep track of the route itself as well as the fraction of people it represents. To do this conveniently, the matrix P is "tagged" by multiplying each row by the symbol for that state as follows:

$$P = P(1) = \begin{array}{c} \\ C \\ T \\ X \\ S \\ G_1 \\ G_2 \end{array} \begin{array}{c} \begin{array}{cccccc} C & T & X & S & G_1 & G_2 \end{array} \\ \begin{bmatrix} 0 & \alpha_1 C & \alpha_2 C & 0 & 0 & 0 \\ 0 & 0 & T & 0 & 0 & 0 \\ 0 & 0 & 0 & \beta_1 X & 0 & \beta_2 X \\ 0 & 0 & 0 & 0 & S & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{array} \tag{3-57}$$

After calculating the P(n), the p_{CG_1} and p_{CG_2} elements of each transition matrix are examined. For this example they are:

$$p_{CG_1}(1) = 0 \qquad p_{CG_2}(1) = 0$$

$$p_{CG_1}(2) = 0 \qquad p_{CG_2}(2) = (\alpha_2\beta_2)CXG_2$$

$$p_{CG_1}(3) = (\alpha_2\beta_1)CXSG_1 \qquad p_{CG_2}(3) = (\alpha_1\beta_2)CTXG_2$$

$$p_{CG_1}(4) = (\alpha_1\beta_1)CTXSG_1 \qquad p_{CG_2}(n > 3) = 0$$

$$p_{CG_1}(n > 4) = 0$$

Notice, for example, that $p_{CG_1}(4) = (\alpha_1\beta_1)CTXSG_1$. This can be interpreted to mean that a $(\alpha_1\beta_1)$ fraction of the people moved from the Curb (C) to Gate 1 (G_1) in exactly 4 steps via the states: Curb (C) to Tickets (T) to Security (X) and Seats (S) and then to the gate (G1). Thus

$$\sum_n p_{CG_1}(n) = \text{All routes between the curb and Gate 1 and fraction of people traveling each route.}$$

Thus, the routes to be considered in this example are given by:

$$[CG_1] = (\alpha_2\beta_1)CXSG_1 + (\alpha_1\beta_1)CTXSG_1 \qquad (3\text{-}58)$$

$$[CG_2] = (\alpha_2\beta_2)CXG_2 + (\alpha_1\beta_2)CTXG_2 \qquad (3\text{-}59)$$

Each symbol used in a route indicates that that service was used and hence involved the associated delay and service time, as well as a travel time between states. For this example, a queuing model for each state has been selected and the per passenger service times and delays have been calculated. The average times spent traveling between states in the routes in the network are arbitrarily selected as:

CT = 2 min	XG_2 = 2 min
CX = 3 min	XS = 1 min
TX = 2 min	SG_1 = 1 min

Passenger flow splits are selected as:

$$\lambda = 56.0 \text{ passengers/minute} \qquad \beta_1 = 0.50$$

$$\alpha_1 = 0.25 \qquad \beta_2 = 0.50$$

$$\alpha_2 = 0.75$$

The hypothetical data which were selected to generate numerical results are shown in Table 3-5. Table 3-6 gives the resulting tabulations. Note that for the numerical example presented there is very little delay time per passenger.

This procedure provides a convenient, efficient technique for computing all of the parameters of interest: passenger processing time (walking or travel time and service time) and passenger delay time. These parameters can be computed for each type of passenger or for each gate or concourse or for each airline. The critical areas (greatest delay) are readily identifiable. Also, this method can be easily implemented in the computer.

Network Analysis

The computer network analysis routines compute the per passenger expected values of time (service, travel and delay) accumulated in a system with n linked queuing systems (components). The primary outputs of the program are four n x n matrices in which the mean accumulated service, delay, travel and total times are contained. The entry (i, j) of each matrix is interpreted as the expected value of time accrued by a passenger moving from state i to state j, regardless of the path taken from i to j. As

TABLE 3-5. HYPOTHETICAL DATA FOR NETWORK EXAMPLE.

State	Curb	Tickets	Security	Seats	Gate 1	Gate 2
Model	M/M/6	M/M/10	M/M/1	M/M/5	M/M/1	M/M/1
Arrivals (pax/min)	56(λ)	14($\alpha_1 \lambda$)	56(λ)	28($\beta_1 \lambda$)	28($\beta_1 \lambda$)	28($\beta_2 \lambda$)
Service μ(pax/min)	360	2	100	10	100	100
$\rho = \lambda/\mu k$	0.03	0.70	0.56	0.56	0.28	0.28
Delay (min/pax)	8.22×10^{-12}	3.69×10^{-2}	1.27×10^{-2}	8.61×10^{-3}	3.89×10^{-3}	3.89×10^{-3}
Service (min/pax)	0.003	0.50	0.01	0.10	0.01	0.01

TABLE 3-6. NUMERICAL RESULTS FOR NETWORK ANALYSIS EXAMPLE 1.

	Fraction of Pax	Travel Time (min)	Service Time* (min/pax)	Total Processing Time (min/pax)	Delay Time (min/pax)	Total Delay Time (min)
Regular Passengers						
$(\alpha_2\beta_1)CX$	0.375	3.0	$\begin{cases}0.003\ (C)\\0.01\ (X)\end{cases}$	1.1299	0.0127	0.00476
$(\alpha_2\beta_1)XS$	0.375	1.0	0.10 (S)	0.4125	0.0086	0.00323
$(\alpha_2\beta_1)SG_1$	0.375	1.0	0.01 (G_1)	0.3788	0.0039	0.00146
$(\alpha_1\beta_1)CT$	0.125	2.0	$\begin{cases}0.003\ (C)\\0.50\ (T)\end{cases}$	0.3129	0.0369	0.00461
$(\alpha_1\beta_1)TX$	0.125	2.0	0.01 (X)	0.2512	0.0127	0.00159
$(\alpha_1\beta_1)XS$	0.125	1.0	0.10 (S)	0.1375	0.0086	0.00108
$(\alpha_1\beta_1)SG_1$	0.125	1.0	0.01 (G_1)	0.1262	0.0039	0.00049
				2.7490		0.01722
	Average Time/Pax 2.75 min Processing + 0.02 min Delay = 2.77 min Total					
Shuttle Passengers						
$(\alpha_2\beta_2)CX$	0.375	3.0	$\begin{cases}0.003\ (C)\\0.01\ (X)\end{cases}$	1.2988	0.0127	0.00476
$(\alpha_2\beta_2)XG_2$	0.375	2.0	0.01 (G_2)	0.7538	0.0039	0.00146
$(\alpha_1\beta_2)CT$	0.125	2.0	$\begin{cases}0.003\ (C)\\0.50\ (T)\end{cases}$	0.3129	0.0369	0.00461
$(\alpha_1\beta_2)TX$	0.125	2.0	0.01 (X)	0.2512	0.0127	0.00159
$(\alpha_1\beta_2)XG_2$	0.125	2.0	0.01 (G_2)	0.2512	0.0039	0.00049
				2.8679		0.01291
	Average Time/Pax 2.87 min Processing + 0.01 min Delay = 2.88 min Total					
	Total for Airport: 2.81 min/pax Processing + 0.02 min/pax Delay = 2.83 min/pax Total					

*The service used is indicated in parentheses. Refer to Figure 3-13.

before, a state in this analysis is a component in the network. Inputs are the expected delay and service times per passenger for each state i, the matrix of travel times for route (i, j), and P, the probability transition matrix.

The implemented algorithm can be derived as follows: Define (i, j, k) as a route from state i to j in k steps. It can be shown that P and its powers contain the probabilities for all routes, $1 \le i,\ j \le n;\ 1 \le k$; that is, the (i, j)th entry of P^k, denoted $p_{ij}(k)$, is the probability of moving from i to j in exactly k steps.

For the landside analysis, when there are no internal "feedback" loops, it can be shown that the only cases of interest are for $1 \le k \le n - 1$. Thus, the entries of P^k over all k are the probabilities of the elements of the sample space

$$S_U = \{\text{all routes } (i, j, k),\ 1 \le i,\ j \le n,\ 1 \le k \le n - 1\} \tag{3-60}$$

Define a set of sample spaces $\{S_{ij},\ 1 \le i,\ j, \le n\}$ such that for a given I, J

$$S_{IJ} = \{\text{all routes } (I, J, k), \text{ for any } k,\ 1 \le k \le n - 1\} \tag{3-61}$$

Note that

$$\bigcup_{\substack{I=1 \\ J=1}}^{n} (S_{IJ}) = S_U \tag{3-62}$$

where the symbol U refers to the "union" or collection of the set of sample spaces. Given I and J, each element of S_{IJ} is a probability which is defined as

$$s_{ij}(k) = \Pr\left\{\text{route } (I, J, k) \;\middle|\; \begin{array}{l}\text{given that a move from i to j} \\ \text{does occur eventually}\end{array}\right\} \tag{3-63}$$

This can be calculated using the rules for conditional probability with the following definition

$$p_{ij} = \sum_{k=1}^{n-1} p_{ij}(k) \tag{3-64}$$

where p_{ij} is the probability that a move from i to j does eventually occur. That is, the probability of a move from i to j is the sum of the probabilities of all the mutually exclusive routes for different k from i to j. Now apply the conditional probability definition to obtain

$$s_{ij}(k) = \frac{p_{ij}(k)}{p_{ij}} \tag{3-65}$$

For a given i and j, every element of S_{ij} has a time (e.g., delay) associated with the route (i, j); this is the time accumulated in moving from i to j in exactly k steps, and has probability $s_{ij}(k)$. For each i, j, define the event space of times

$$T_{ij} = \{t_k, k = 1, 2, \ldots, n - 1\} \tag{3-66}$$

and the random variable X_{ij} with domain T_{ij} such that

$$P_{X_{ij}}(t_k) = \Pr\{X_{ij} = t_k\} = s_{ij}(k) \tag{3-67}$$

For our problem the t_k's are the times of interest--travel time, delay time, and service time--and $P_{X_{ij}}(t_k)$ is the fraction of passengers (probability) who incur that amount of time. Note that

$$\sum P_{X_{ij}}(t_k) = \sum s_{ij}(k) = \frac{\sum_k p_{ij}(k)}{p_{ij}} = 1 \tag{3-68}$$

The expected value of X for a given i and j is obtained by

$$\begin{aligned} E(X) &= \sum_k t_k \cdot P_{X_{ij}}(t_k) \\ &= \sum_k t_k \cdot s_{ij}(k) \\ &= \frac{\sum_k t_k \cdot p_{ij}(k)}{p_{ij}} \end{aligned} \tag{3-69}$$

This is the value calculated in the program for all i, j, $1 \leq i, j \leq n$, and for service, delay, and travel time random variables. At each step k, the values $(t_k \cdot p_{ij}(k))$ are computed and summed with previous (i, j)th entry of the appropriate matrix. The final step is to divide each (i, j)th entry by p_{ij} so that each matrix element is an expected value of time obtained over that portion of the population that traveled from i to j.

SECTION 4

PROGRAM DESCRIPTION

A general description of the landside analysis program is presented in this section. Included is an overview of the program flow and control followed by an annotated sample output. Finally, a description of the airport data base developed under this study is presented.

4.1 PROGRAM FLOW AND CONTROL

For most airports of interest, the number of landside components required in the model is very large (over 100). It is computationally more efficient and the output is more understandable if the problem is divided into parts. The approach taken to analyze the airport landside system first divides the landside system as follows:

- The airport landside is separated into one or more terminal units according to the physical and functional division of the roadway network.
- Each terminal unit is further separated into terminal zones according to the physical and functional division of the passenger terminals.
- Each terminal zone is separated into an enplaning and deplaning passenger flow.

For the demand and control parameters specified, the airport landside is analyzed by reversing the above development. The enplaning and deplaning flows for each zone are analyzed by the methods described in Section 3. The results for each zone within an area are combined and the groundside networks for each zone are analyzed. Finally, the terminal units are combined to obtain results for the entire airport landside. This method is illustrated by considering as an example Boston Logan Airport. As outlined above, the landside is first mapped as a combination of (groundside) terminal units as shown in Figure 4-1 according to the roadway system. Next, each terminal unit is divided into terminal zones as shown in Figure 4-2. Finally, each terminal zone is divided into an enplaning and deplaning flow as shown in Figure 4-3.

An examination of Figures 4-1, 4-2, and 4-3 indicates the amount of information required at a large hub airport. The details of each component must be specified (number of ticket counters, baggage claim devices, etc.), as well as all the possible links between the components (the network), the distances along each link and the fraction of passengers traveling each link. In addition, on the roadway, the vehicle modal splits at

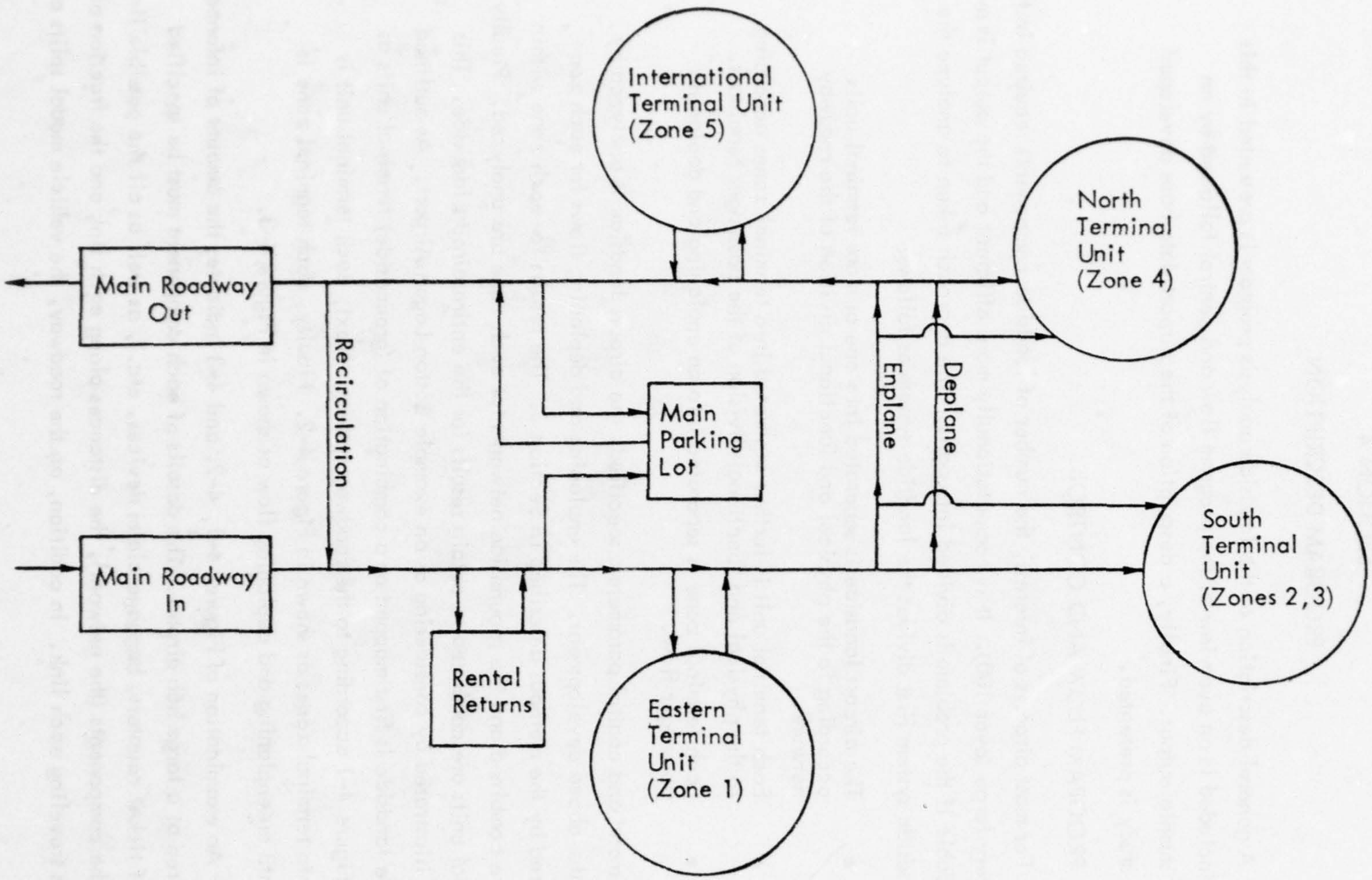

FIGURE 4-1. TYPICAL ROADWAY NETWORK--BOSTON LOGAN AIRPORT.

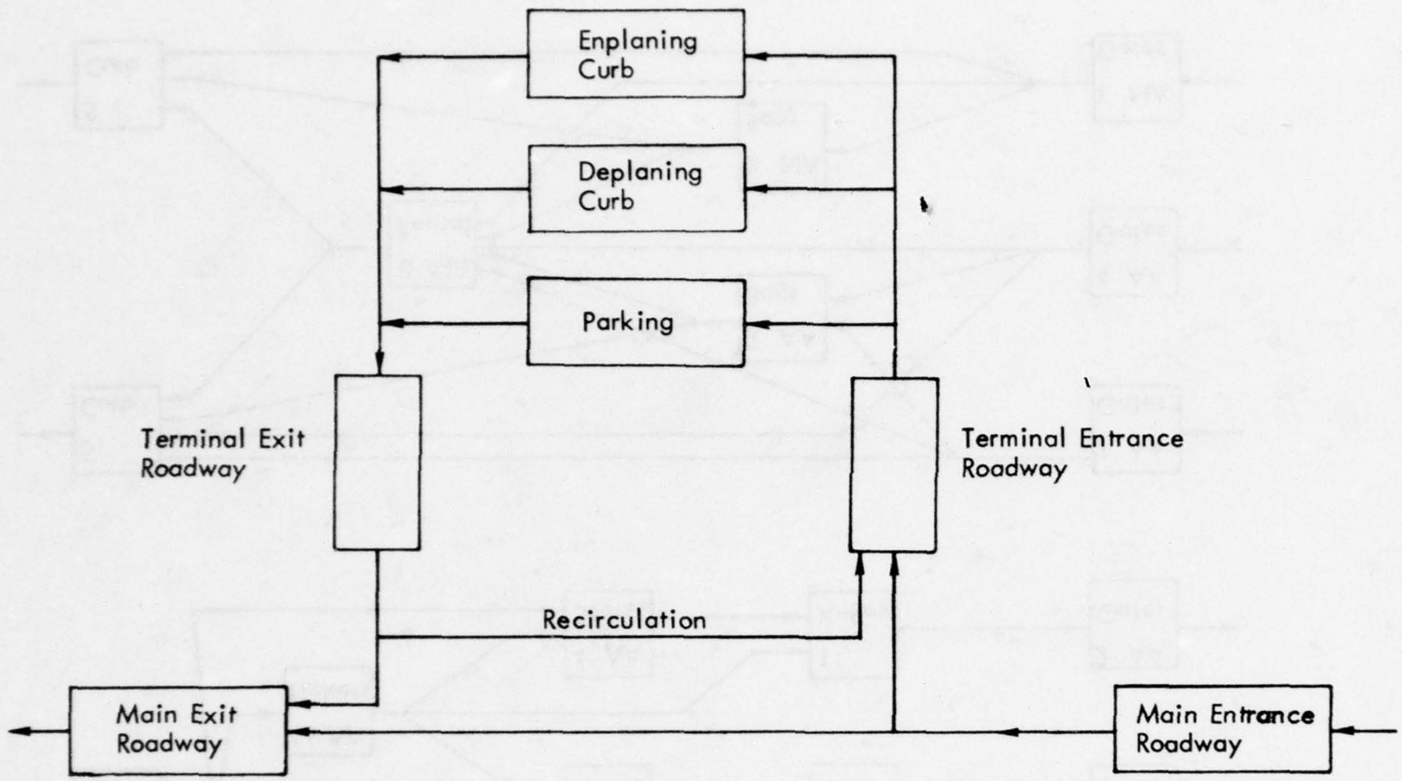

FIGURE 4-2. SAMPLE TERMINAL UNIT--SOUTH TERMINAL--BOSTON LOGAN AIRPORT

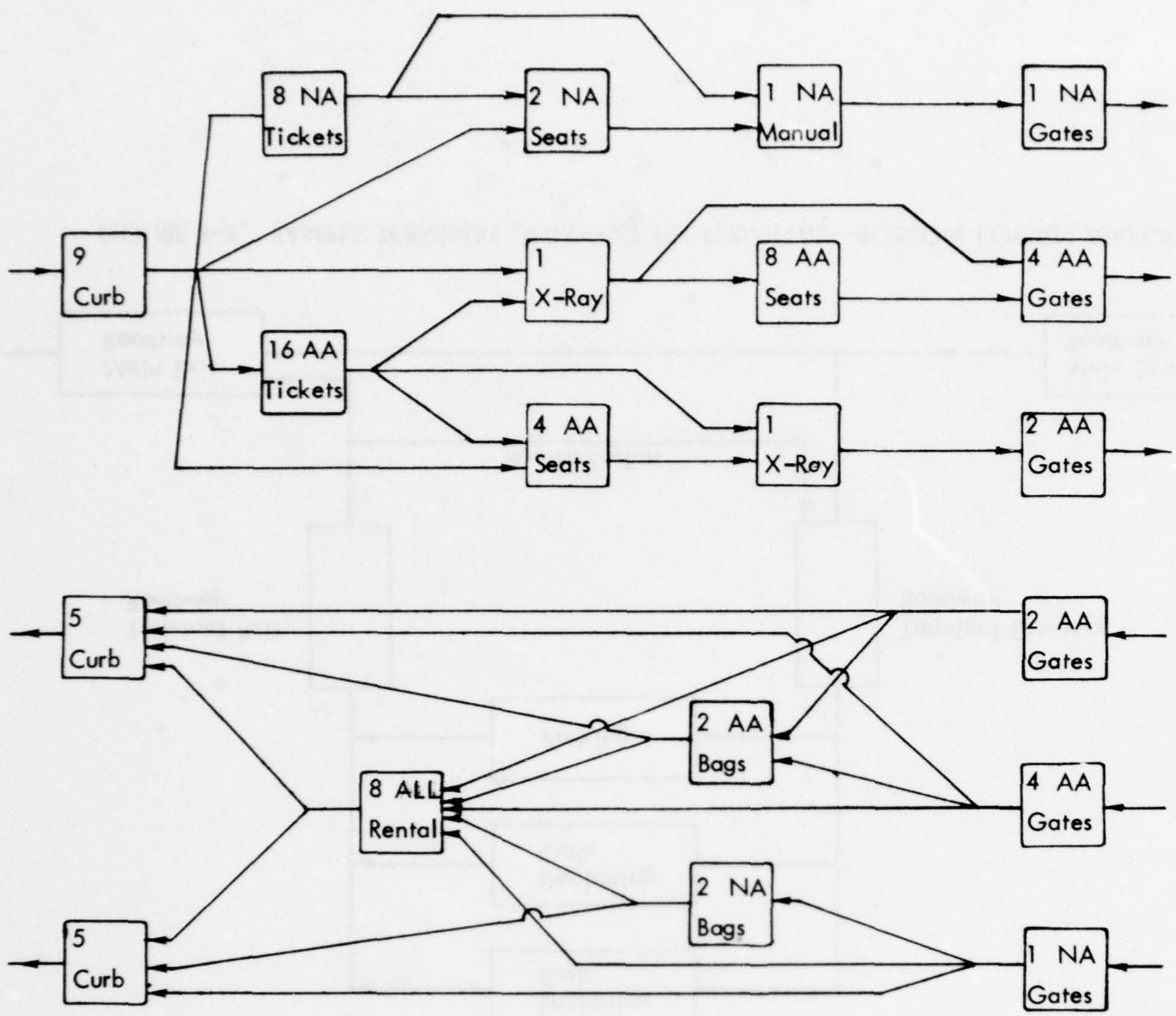

FIGURE 4-3. SAMPLE TERMINAL ZONE -- AMERICAN, NATIONAL AIRLINES TERMINAL -- BOSTON LOGAN AIRPORT

each point are required. This specifies the airport landside system; to determine the delays, the input demands must be determined (number of passengers, modal split, etc., as indicated in Subsection 3.2). For a typical large hub airport, the number of data items required can easily exceed 1,000.

4.2 AIRPORT LANDSIDE DATA BASE

As part of the effort performed under this study, a data base of airport landside elements has been compiled for the large hub airports. The information for each airport is in a format compatible with the landside analysis computer programs. Six of the large hub airports are modeled in extensive detail to obtain maximum accuracy from the analysis; the remaining airport data is compiled from readily available documents primarily References 1, 22, 23 and 25) and should be considered as conceptually operable but not analytically precise. A list of the airports included in the data base is presented in Table 4-1.

TABLE 4-1. AIRPORTS INCLUDED IN AIRPORT LANDSIDE DATA BASE.

Atlanta (ATL)	New Orleans (MSY)
Boston (BOS)*	New York-Kennedy (JFK)
Chicago O'Hare (ORD)	New York-LaGuardia (LGA)*
Cleveland (CLE)	Newark (EWR)
Dallas-Ft. Worth (DFW)	Philadelphia (PHL)
Denver (DEN)*	Phoenix (PHX)
Detroit (DTW)*	Pittsburgh (PIT)
Houston (IAH)	St. Louis (STL)
Kansas City (MCI)	San Francisco (SFO)*
Las Vegas (LAS)	Seattle (SEA)
Los Angeles (LAX)	Tampa (TPA)
Miami (MIA)*	Washington-National (DCA)
Minneapolis (MSP)	Washington-Dulles (IAD)

*Airport landside modeled in extensive detail.

Except for the airports modeled in detail, most of the data are taken from Reference 1. The other sources are used only when the required information is not included in Reference 1. Plans of the airports are also used primarily for determining the roadway distances and in some cases the curb lengths. The geometry of the terminal is, of course, an important item in determining the division into terminal units and zones. As a rule, when several separate terminals make up the landside of an airport (for example, New York-Kennedy), each one is modeled separately. When, on the other hand, there is one main terminal, each pier or satellite is usually treated as a separate terminal unit. Special consideration is given to international traffic. In almost all cases, the enplaning and deplaning of international passengers is assumed to take place in a separate terminal.

One assumption in the development of the data base is that the distances between various components inside the terminal do not vary significantly from one airport to the other. There are two reasons for this simplification. First, except for the airports for which very detailed floor plans of the terminals are available, and on-site inspections were made, these distances are not available. Second, even if detailed plans are used to estimate the distances, some approximations must still be made. For example, since there are numerous physical routes for passengers to take within any given area, this usually entails representing several paths with one or two simpler "average" routes. However, even though walking distances account for a substantial part of the time and inconvenience of passengers in airports, they do not contribute to the delays caused by congestion.

A final source of error is introduced when data on some aspect of the landside operation are missing completely. In such cases (a good example of which is the average time in the parking lot) some nationwide average number is used.

Overall, the data base developed is a reasonable representation of the airport landside, especially for the six airports modeled in detail. As noted in Subsection 4.1, the complete specification of the landside of a particular air carrier airport requires several hundred data items. Nevertheless, it is believed that the information included in the data base will yield acceptably accurate results.

4.3 SAMPLE OUTPUT

A sample of the landside analysis program computer output is presented as Figure 4-4 and is discussed in this subsection. The first items output are the airport name, dates of the data, and the airport control parameters. As discussed in Subsection 3.2, there are several ways to derive the hourly demand used by the program; the one selected by the user is indicated as noted in Figure 4-4.

Also indicated on the first page are the number of terminal units and terminal zones (Subsection 4.1) and the passenger splits at each terminal zone. The average number of passengers per vehicle, number of bags carried per passenger, the total length of curb frontage, roadway capacity, and number of public parking spaces are all listed as well.

For each terminal zone, the enplaning and deplaning passenger flows are analyzed. As shown in Figure 4-4, this consists of first printing the major airlines within the zone. Next, a table is output which represents the results of the flow analysis. The first column of the table identifies each state in the network; a state is a component in the system. For example, in Figure 4-3, the American/National terminal zone is modeled with twelve enplaning states and eight deplaning states. The second column indicates the particular model (see Subsection 3.3) implemented to represent each state. This is followed by the number of servers at each state according to the model used. Next the passenger arrival rate is noted; this is determined from the airport hourly demand total, the fraction of passengers using the terminal unit, and the flow analysis of the network. The total service capacity of the facility is then indicated. This is the average service rate per server times the number of independent servers at the facility.

The utilization factor is the ratio of the total arrival rate to the total service rate. A number greater than one indicates that passengers are arriving at a rate greater than the handling capacity of the facility. For these saturated component states an asterisk is printed to indicate the situation and to note that the excess delay is estimated by the technique presented in Subsection 3.2. Also, the output rate of passengers at these facilities can, of course, be no greater than the total service rate. This implies that the input rate at a subsequent facility is less than if there was no saturation.

The per passenger delay is the primary output of each of the component models as discussed in Subsection 3.3. The total peak hour delay is the per passenger delay multiplied by the hourly expected arrival rate of passengers at each facility.

Following this table, a summary of the analysis of each network system is presented as shown in Figure 4-4. The passenger processing times (delay, service, travel, and total) are printed for the peak hours as well as the cumulative passenger times for this peak hour period. These are the times incurred in proceeding through the entire network system. These cumulative passenger times are the per passenger times multiplied by the total number of passengers expected during this hour. The annual times are estimated from the hourly times by the methods indicated in Subsection 3.2.

It is important to note that the passenger processing times listed in this subsection are not the simple sums of the times for each component listed in the preceding table. For example, even if the per passenger delay at a ticket counter is two minutes, the average per passenger delay through that terminal zone may be less than two minutes if only a small fraction of the total passengers use that ticket counter. The analysis used to determine these figures is relatively complex and is developed in Subsection 3.4.

Following this analysis, results for first the deplaning then the enplaning flows for each terminal zone within a terminal unit are presented. Then the groundside analysis of the terminal unit is conducted. As shown in Figure 4-4, the output format is very similar to the passenger analysis output and thus largely self-explanatory. The groundside analysis is somewhat different than the terminal analysis since flows are in terms of vehicles. The special methods used are noted in Subsection 3.3.3.

The final page of output is the airport summary. Here the delays and total times (including delays) for each terminal unit in the airport are repeated. An overall airport average is computed and printed as well; this average is weighted by the percentage of passengers using each terminal unit.

FIGURE 4-4

SAMPLE LANDSIDE ANALYSIS PROGRAM OUTPUT - BOSTON LOGAN AIRPORT

LOGAN INTERNATIONAL AIRPORT --BOS-- '76-'77 DATA

A.	ANNUAL PASSENGER ENPLANEMENTS(000):	5250.
B.	PEAK HOUR PASSENGERS:	5000.
C.	FLEET MIX:	10% WIDE-BODIES
D.	AIRPORT ACTIVITY DESCRIPTORS:	2 PEAK 7.3
E.	CONNECTING PAX:	15%
F.	PEAK HOUR AIRCRAFT OPERATIONS:	70
G.	AVERAGE AIRCRAFT LOAD FACTOR:	50%
		AUTO TAXI BUS RAIL
H.	PASSENGER MODAL SPLIT:	(0.82,0.06,0.01,0.11)

THE PRIMARY CONTROL PARAMETER FOR THIS RUN IS B

NUMBER OF TERMINAL UNITS:	4
NUMBER OF TERMINAL ZONES:	5
PASSENGER SPLIT AT EACH:	0.26
	0.18
	0.15
	0.35
	0.06
AVERAGE NUMBER OF PAX PER VEHICLE:	1.0
AVERAGE NUMBER OF BAGS PER PAX:	1.5
TOTAL AIRPORT CURB FRONTAGE:	5585.
AIRPORT ROADWAY CAPACITY(VEH/HR):	3600.
TOTAL NUMBER OF PARKING SPACES:	7777.

PEAK HOUR PASSENGERS (MIN)

	DEPLANING PAX DELAY	DEPLANING PAX TOTAL	ENPLANING PAX DELAY	ENPLANING PAX TOTAL
TERMINAL UNIT # 1 (26%)	16.7	23.0	23.4	30.5
TERMINAL UNIT # 2 (33%)	17.7	24.3	21.1	29.2
TERMINAL UNIT # 3 (35%)	36.5	43.7	32.3	40.7
TERMINAL UNIT # 4 (6%)	12.9	21.2	53.9	62.3
AIRPORT AVERAGE	23.7	30.6	27.6	35.5

****
DATA FOR TERMINAL UNIT # 1
****

EASTERN,NORTHWEST ORIENT AIRLINES -----DEPLANING-----

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
GATE	MMK	6	0.14	6.00	0.02	0.	0.0
GATE	MMK	6	0.14	6.00	0.02	0.	0.0
BAGS	BAGS	5	0.16	1.50	0.11	965.	15681.2
RENT	MGK	4	0.02	0.03	0.74	37.	606.7
RENT	MGK	4	0.02	0.03	0.74	37.	606.7
CURB	MGK	7	0.27	0.47	0.58	0.	7.5

	PEAK HOUR		ANNUAL
DELAY TIME:	9.7 MIN	9505. PAX-MIN	13972048. MIN
SERVICE TIME:	0.7 MIN	648. PAX-MIN	3403977. MIN
TRAVEL TIME:	3.4 MIN	3296. PAX-MIN	17301376. MIN
TOTAL TIME:	13.8 MIN	13449. PAX-MIN	34677404. MIN

EASTERN, NORTHWEST ORIENT AIRLINES -----ENPLANING-----

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
CURB	MGK	6	0.27	0.40	0.68	1.	23.6
TIX	MMK	2	0.00	0.03	0.10	1.	12.4
TIX	MMK	13	0.08	0.17	0.45	0.	1.3
XRAY	MGK	1	0.14	0.06	2.30 *	1012.	16445.7
SEAT	MMK	12	0.04	0.30	0.15	0.	0.0
GATE	MMK	6	0.06	6.00	0.01	0.	0.0
SEAT	MMK	12	0.04	0.30	0.12	0.	0.0
XRAY	MGK	1	0.10	0.06	1.66 *	723.	11754.4
GATE	MMK	6	0.06	6.00	0.01	0.	0.0

	PEAK HOUR		ANNUAL
DELAY TIME:	14.9 MIN	14504. PAX-MIN	21321436. MIN
SERVICE TIME:	1.4 MIN	1326. PAX-MIN	6962175. MIN
TRAVEL TIME:	3.5 MIN	3405. PAX-MIN	17877968. MIN
TOTAL TIME:	19.7 MIN	19236. PAX-MIN	46161580. MIN

EASTERN, NORTHWEST ORIENT AIRLINES -----ROADWAY-----

	AUTOS	TAXIS	BUSES	RAIL
PASSENGER MODAL SPLIT:	0.82	0.06	0.01	0.11
VEHICLE MODAL SPLIT:	0.95	0.04	0.00	0.01
PAX PER VEHICLE-BY-TYPE:	0.9	1.7	10.0	10.0

DEPLANING CURB FRONTAGE: 780. FT
ENPLANING CURB FRONTAGE: 672. FT

STATE	MODEL	RATE IN (VEH/HR)	TOTAL SERVICE (VEH/HR)	UTILIZATION FACTOR	PER PAX DELAY (SEC)	TOTAL PAX-HR OF DELAY (PEAK HOUR)
RDWY IN	ROAD	4973.	3600.	1.4 *	94.7	29.05
TMRD IN	ROAD	1294.	1800.	0.7	3.0	0.91
RNTL DEP	MQK	172.	240.	2.8 *	1365.8	419.22
DE-CURB	CURB	144.	640.	0.2	0.0	0.00
EN-CURB	CURB	262.	840.	0.3	0.0	0.00
PARKING	PARK	1066.	2022.	0.5	315.2	96.76
TMRD OUT	ROAD	1294.	1800.	0.7	3.0	0.91
RDWY OUT	ROAD	4973.	3600.	1.4 *	148.7	45.66

-----DEPLANING ROADWAY SUMMARY-----

	PEAK HOUR		ANNUAL
DELAY TIME:	7.2 MIN	100. PAX-HRS	146948. HRS
SERVICE TIME:	2.7 MIN	37. PAX-HRS	235. HRS
TOTAL TIME:	9.9 MIN	137. PAX-HRS	147182. HRS

-----ENPLANING ROADWAY SUMMARY-----

	PEAK HOUR		ANNUAL
DELAY TIME:	9.4 MIN	130. PAX-HRS	191427. HRS
SERVICE TIME:	3.0 MIN	42. PAX-HRS	266. HRS
TOTAL TIME:	12.5 MIN	172. PAX-HRS	191693. HRS

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PEAK HOUR TOTALS FOR TERMINAL UNIT # 1 (MIN)

	DEPLANING PAX		ENPLANING PAX	
	DELAY	TOTAL	DELAY	TOTAL
TERMINAL	9.7	14.2	14.9	19.7
ROADWAY	7.2	9.9	9.4	12.5
COMBINED	15.9	22.6	22.9	30.3

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****
DATA FOR TERMINAL UNIT # 2
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AMERICAN AIRLINES, NATIONAL AIRLINES ------DEPLANING------

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
GATE	MMK	2	0.06	2.00	0.03	0.	0.0
GATE	MMK	4	0.11	4.00	0.03	0.	0.0
GATE	MMK	1	0.01	1.00	0.01	0.	0.2
BAGS	BAGS	4	0.10	1.20	0.09	786.	8843.9
BAGS	BAGS	2	0.01	0.60	0.02	372.	4179.4
RENT	MGK	8	0.03	0.05	0.51	1.	15.1
CURB	MGK	5	0.16	0.33	0.48	0.	4.7
CURB	MGK	5	0.03	0.33	0.08	0.	0.0

	PEAK HOUR		ANNUAL
DELAY TIME:	7.5 MIN	5089. PAX-MIN	7480441. MIN
SERVICE TIME:	0.7 MIN	449. PAX-MIN	2356606. MIN
TRAVEL TIME:	3.4 MIN	2280. PAX-MIN	11967777. MIN
TOTAL TIME:	11.6 MIN	7817. PAX-MIN	21804824. MIN

AMERICAN AIRLINES, NATIONAL AIRLINES -----ENPLANING-----

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR		PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
CURB	MGK	9	0.19	0.60	0.31		0.	0.0
TIX	MMK	8	0.00	0.11	0.03		0.	0.0
TIX	MMK	16	0.05	0.22	0.24		0.	0.0
SEAT	MMK	2	0.01	0.05	0.23		2.	25.7
XRAY	MGK	1	0.11	0.06	1.91	*	836.	9405.4
SEAT	MMK	4	0.05	0.10	0.46		2.	28.0
XRAY	MGK	1	0.01	0.06	0.25		3.	32.3
SEAT	MMK	8	0.04	0.20	0.20		0.	0.0
XRAY	MGK	1	0.06	0.06	0.99	*	422.	4748.9
GATE	MMK	1	0.01	1.00	0.01		0.	0.2
GATE	MMK	4	0.06	4.00	0.01		0.	0.0
GATE	MMK	2	0.06	2.00	0.03		0.	0.0

	PEAK HOUR		ANNUAL
DELAY TIME:	10.7 MIN	7202. PAX-MIN	10586818. MIN
SERVICE TIME:	1.4 MIN	941. PAX-MIN	4937679. MIN
TRAVEL TIME:	4.5 MIN	3021. PAX-MIN	15862756. MIN
TOTAL TIME:	16.5 MIN	11164. PAX-MIN	31387254. MIN

ALLEGHENY AIRLINES ------DEPLANING------

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
GATE	MMK	4	0.06	4.00	0.02	0.	0.0
GATE	MMK	6	0.09	6.00	0.02	0.	0.0
BAGS	BAGS	2	0.09	0.60	0.16	1236.	11584.0
RENT	MGK	6	0.02	0.04	0.57	5.	46.3
CURB	MGK	4	0.16	0.27	0.59	2.	14.3

	PEAK HOUR		ANNUAL
DELAY TIME:	12.4 MIN	6971. PAX-MIN	10248032. MIN
SERVICE TIME:	0.7 MIN	374. PAX-MIN	1963833. MIN
TRAVEL TIME:	5.8 MIN	3277. PAX-MIN	17201954. MIN
TOTAL TIME:	18.9 MIN	10622. PAX-MIN	29413820. MIN

ALLEGHENY AIRLINES -----ENPLANING-----

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
CURB	MGK	4	0.16	0.27	0.59	2.	14.3
TIX	MMK	20	0.04	0.27	0.16	0.	0.0
XRAY	MGK	1	0.14	0.06	2.36 *	1040.	9751.5
SEAT	MMK	4	0.02	0.10	0.24	0.	2.1
SEAT	MMK	6	0.04	0.15	0.24	0.	0.3
XRAY	MGK	1	0.02	0.06	0.26	3.	28.5
GATE	MMK	4	0.02	4.00	0.01	0.	0.0
GATE	MMK	6	0.04	6.00	0.01	0.	0.0
GATE	MMK	1	0.02	1.00	0.02	0.	0.1

	PEAK HOUR		ANNUAL
DELAY TIME:	15.6 MIN	8794. PAX-MIN	12927783. MIN
SERVICE TIME:	1.5 MIN	833. PAX-MIN	4374962. MIN
TRAVEL TIME:	5.3 MIN	3002. PAX-MIN	15762305. MIN
TOTAL TIME:	22.5 MIN	12630. PAX-MIN	33065052. MIN

AMERICAN, NATIONAL, ALLEGHENY AIRLINES -----ROADWAY-----

	AUTOS	TAXIS	BUSES	RAIL
PASSENGER MODAL SPLIT:	0.82	0.06	0.01	0.11
VEHICLE MODAL SPLIT:	0.95	0.04	0.00	0.01
PAX PER VEHICLE-BY-TYPE:	0.9	1.7	10.0	10.0

DEPLANING CURB FRONTAGE: 990. FT
ENPLANING CURB FRONTAGE: 853. FT

STATE	MODEL	RATE IN (VEH/HR)	TOTAL SERVICE (VEH/HR)	UTILIZATION FACTOR	PER PAX DELAY (SEC)	TOTAL PAX-HR OF DELAY (PEAK HOUR)
RDWY IN	ROAD	4973.	3600.	1.4 *	118.3	46.10
TMRD IN	ROAD	1643.	2700.	0.6	4.8	1.86
RNTL DEP	MGK	219.	240.	2.8 *	1365.8	532.08
DE-CURB	CURB	183.	960.	0.2	0.0	0.00
EN-CURB	CURB	333.	1230.	0.3	0.0	0.00
PARKING	PARK	1353.	2566.	0.5	400.1	155.88
TMRD OUT	ROAD	1643.	2700.	0.6	4.8	1.86
RDWY OUT	ROAD	4973.	3600.	1.4 *	131.8	51.36

-----------------------DEPLANING ROADWAY SUMMARY-----------------------

	PEAK HOUR		ANNUAL
DELAY TIME:	8.4 MIN	148. PAX-HRS	217444. HRS
SERVICE TIME:	2.4 MIN	43. PAX-HRS	212. HRS
TOTAL TIME:	10.9 MIN	190. PAX-HRS	217656. HRS

-----------------------ENPLANING ROADWAY SUMMARY-----------------------

	PEAK HOUR		ANNUAL
DELAY TIME:	8.8 MIN	154. PAX-HRS	226732. HRS
SERVICE TIME:	3.1 MIN	54. PAX-HRS	272. HRS
TOTAL TIME:	11.9 MIN	209. PAX-HRS	227004. HRS

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PEAK HOUR TOTALS FOR TERMINAL UNIT # 2 (MIN)

	DEPLANING PAX		ENPLANING PAX	
	DELAY	TOTAL	DELAY	TOTAL
TERMINAL	9.7	14.9	12.9	19.2
ROADWAY	8.4	10.9	8.8	11.9
COMBINED	16.9	24.1	20.4	29.3

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DATA FOR TERMINAL UNIT # 3
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TWA, DELTA, UNITED AIRLINES -----DEPLANING-----

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
GATE	MMK	7	0.08	7.00	0.01	0.	0.0
GATE	MMK	10	0.20	10.00	0.02	0.	0.0
GATE	MMK	2	0.08	2.00	0.04	0.	0.0
BAGS	BAGS	2	0.05	0.60	0.08	700.	15305.7
BAGS	BAGS	1	0.12	0.30	0.41	3282.	71804.7
BAGS	BAGS	2	0.05	0.60	0.08	700.	15305.7
RENT	MGK	13	0.05	0.09	0.61	1.	25.5
CURB	MGK	3	0.36	0.20	1.82 *	530.	11587.1

	PEAK HOUR		ANNUAL
DELAY TIME:	30.3 MIN	39758. PAX-MIN	58444124. MIN
SERVICE TIME:	0.7 MIN	873. PAX-MIN	4582278. MIN
TRAVEL TIME:	5.5 MIN	7201. PAX-MIN	37807256. MIN
TOTAL TIME:	36.4 MIN	47832. PAX-MIN	100833664. MIN

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TWA, DELTA, UNITED AIRLINES -----ENPLANING-----

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
CURB	MGK	5	0.36	0.33	1.09 *	140.	3068.6
TIX	MMK	10	0.02	0.13	0.12	0.	0.0
TIX	MMK	10	0.06	0.13	0.42	0.	3.5
TIX	MMK	8	0.02	0.11	0.22	0.	0.1
XRAY	MGK	1	0.11	0.06	1.87 *	819.	17909.3
XRAY	MGK	1	0.22	0.06	3.73 *	1655.	36210.8
TIX	MMK	1	0.00	0.01	0.27	27.	588.9
SEAT	MMK	14	0.03	0.35	0.08	0.	0.0
SEAT	MMK	4	0.01	0.10	0.14	0.	0.7
SEAT	MMK	16	0.03	0.40	0.07	0.	0.0
SEAT	MMK	4	0.01	0.10	0.14	0.	0.6
GATE	MMK	7	0.04	7.00	0.01	0.	0.0
GATE	MMK	2	0.02	2.00	0.01	0.	0.0
GATE	MMK	8	0.04	8.00	0.00	0.	0.0
GATE	MMK	2	0.02	2.00	0.01	0.	0.0

	PEAK HOUR		ANNUAL
DELAY TIME:	25.3 MIN	33179. PAX-MIN	48773580. MIN
SERVICE TIME:	1.4 MIN	1832. PAX-MIN	9616266. MIN
TRAVEL TIME:	5.8 MIN	7568. PAX-MIN	39730152. MIN
TOTAL TIME:	32.4 MIN	42579. PAX-MIN	98120000. MIN

TWA, DELTA, UNITED AIRLINES -----ROADWAY-----

	AUTOS	TAXIS	BUSES	RAIL
PASSENGER MODAL SPLIT:	0.82	0.06	0.01	0.11
VEHICLE MODAL SPLIT:	0.95	0.04	0.00	0.01
PAX PER VEHICLE-BY-TYPE:	0.9	1.7	10.0	10.0

DEPLANING CURB FRONTAGE: 1050. FT
ENPLANING CURB FRONTAGE: 905. FT

STATE	MODEL	RATE IN (VEH/HR)	TOTAL SERVICE (VEH/HR)	UTILIZATION FACTOR	PER PAX DELAY (SEC)	TOTAL PAX-HR OF DELAY (PEAK HOUR)
RDWY IN	ROAD	4973.	3600.	1.4 *	135.2	55.87
TMRD IN	ROAD	1489.	1800.	0.8	2.4	0.99
RNTL DEP	MGK	232.	240.	2.8 *	1365.8	564.33
DE-CURB	CURB	166.	880.	0.2	0.0	0.00
EN-CURB	CURB	302.	1110.	0.3	0.0	0.00
PARKING	PARK	1226.	2722.	0.5	310.0	128.09
TMRD OUT	ROAD	1489.	1800.	0.8	2.4	0.99
RDWY OUT	ROAD	4973.	3600.	1.4 *	108.2	44.70

-------------------------DEPLANING ROADWAY SUMMARY-------------------------

	PEAK HOUR		ANNUAL
DELAY TIME:	6.7 MIN	124. PAX-HRS	182202. HRS
SERVICE TIME:	1.9 MIN	34. PAX-HRS	162. HRS
TOTAL TIME:	8.5 MIN	158. PAX-HRS	182364. HRS

-------------------------ENPLANING ROADWAY SUMMARY-------------------------

	PEAK HOUR		ANNUAL
DELAY TIME:	7.4 MIN	137. PAX-HRS	201631. HRS
SERVICE TIME:	3.0 MIN	56. PAX-HRS	263. HRS
TOTAL TIME:	10.4 MIN	193. PAX-HRS	201894. HRS

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PEAK HOUR TOTALS FOR TERMINAL UNIT # 3 (MIN)

	DEPLANING PAX		ENPLANING PAX	
	DELAY	TOTAL	DELAY	TOTAL
TERMINAL	30.3	36.4	25.3	32.4
ROADWAY	6.7	8.5	7.4	10.4
COMBINED	36.0	43.7	31.5	41.3

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DATA FOR TERMINAL UNIT # 4
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INTERNATIONAL TERMINAL-----DEPLANING-----

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
GATE	MMK	9	0.06	9.00	0.01	0.	0.0
BAGS	BAGS	3	0.06	0.90	0.07	588.	2203.1
FIS	MGK	5	0.06	0.08	0.75	55.	207.8
RENT	MGK	10	0.01	0.07	0.14	0.	0.0
CURB	MGK	10	0.06	0.67	0.09	0.	0.0

	PEAK HOUR		ANNUAL
DELAY TIME:	10.7 MIN	2411. PAX-MIN	3544067. MIN
SERVICE TIME:	1.7 MIN	382. PAX-MIN	2004844. MIN
TRAVEL TIME:	6.7 MIN	1500. PAX-MIN	7875000. MIN
TOTAL TIME:	19.1 MIN	4293. PAX-MIN	13423911. MIN

INTERNATIONAL TERMINAL-----ENPLANING-----

STATE	MODEL	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (SEC)	TOTAL PEAK HOUR DELAY (PAX-MIN)
CURB	MGK	10	0.06	0.67	0.09	0.	0.0
TIX	MMK	23	0.06	0.22	0.29	0.	0.0
XRAY	MGK	1	0.06	0.02	2.76 *	2960.	11100.8
GATE	MMK	9	0.02	9.00	0.00	0.	0.0

	PEAK HOUR		ANNUAL
DELAY TIME:	49.3 MIN	11101. PAX-MIN	16318183. MIN
SERVICE TIME:	2.8 MIN	624. PAX-MIN	3274031. MIN
TRAVEL TIME:	5.8 MIN	1313. PAX-MIN	6890625. MIN
TOTAL TIME:	57.9 MIN	13037. PAX-MIN	26482840. MIN

INTERNATIONAL TERMINAL-----ROADWAY-----

	AUTOS	TAXIS	BUSES	RAIL
PASSENGER MODAL SPLIT:	0.82	0.06	0.01	0.11
VEHICLE MODAL SPLIT:	0.95	0.04	0.00	0.01
PAX PER VEHICLE-BY-TYPE:	0.9	1.7	10.0	10.0

COMBINED CURB FRONTAGE: 180. FT

STATE	MODEL	RATE IN (VEH/HR)	TOTAL SERVICE (VEH/HR)	UTILIZATION FACTOR	PER PAX DELAY (SEC)	TOTAL PAX-HR OF DELAY (PEAK HOUR)
RDWY IN	ROAD	4973.	3600.	1.4 *	148.7	10.54
TMRD IN	ROAD	255.	1800.	0.1	1.4	0.10
RNTL DEP	MGK	40.	240.	2.8 *	1365.8	96.74
CMB-CURB	CURB	80.	140.	0.6	8.2	0.58
PARKING	PARK	210.	467.	0.5	53.1	3.76
TMRD OUT	ROAD	255.	1800.	0.1	1.4	0.10
RDWY OUT	ROAD	4973.	2700.	1.8 *	105.0	7.44

----------------DEPLANING ROADWAY SUMMARY----------------

	PEAK HOUR		ANNUAL
DELAY TIME:	2.6 MIN	8. PAX-HRS	12179. HRS
SERVICE TIME:	1.9 MIN	6. PAX-HRS	166. HRS
TOTAL TIME:	4.5 MIN	14. PAX-HRS	12345. HRS

----------------ENPLANING ROADWAY SUMMARY----------------

	PEAK HOUR		ANNUAL
DELAY TIME:	4.5 MIN	14. PAX-HRS	21116. HRS
SERVICE TIME:	2.7 MIN	9. PAX-HRS	237. HRS
TOTAL TIME:	7.2 MIN	23. PAX-HRS	21353. HRS

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PEAK HOUR TOTALS FOR TERMINAL UNIT # 4 (MIN)

	DEPLANING PAX		ENPLANING PAX	
	DELAY	TOTAL	DELAY	TOTAL
TERMINAL	10.7	19.1	49.3	57.9
ROADWAY	2.6	4.5	4.5	7.2
COMBINED	12.9	22.9	53.2	64.1

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SECTION 5
SUMMARY AND RECOMMENDATIONS

In this study an airport landside analysis program was developed and a data base compiled for the United States large hub airports. The airport is treated as consisting of three areas, each identified with a different type of flow:

- Groundside: the roadway system of the airport with a vehicle flow
- Terminal: the passenger flow section of the airport
- Airside: the part of the airport utilized by aircraft and with an aircraft flow

The first two areas of the airport, groundside and terminal, are collectively referred to as the landside and are of primary interest in this study.

Analytic queuing models are used to represent the airport landside. This is a major distinction between this study and the majority of other airport landside studies, which rely primarily on simulation or rule-of-thumb analysis techniques (References 6, 10, 11, 12, and 13). The major assumptions employed in this study include the following:

- The flows, demands, and services are in steady state
- The demand distribution at each airport service (ticketing, security, etc.) can be represented as Poisson
- The arrival rate at each service is independent of the dynamics of any preceding service

Several other assumptions and approximations were necessary in the development of the analysis (including a method to estimate the extra delay at a service facility which has an excess demand). These assumptions are discussed in detail in the body of this report.

The major control inputs to the program are as follows:

- Annual passenger enplanements
- Peak hour enplaning and deplaning passengers
- Passenger modal split
- Percentage of connecting passengers
- Aircraft fleet mix, load factor, peak hour operations

Other airport information data items are specified in this report and include the number and type of each landside facility (ticket counters, baggage claim devices, etc.); for a large hub airport, several hundreds of data items may be required for a complete specification of the airport. In view of this, and to alleviate the burden of implementing the program, a data base for the large hub airports has been developed as part of this study. Except for six airports modeled in detail by on-site visits (Boston, New York-LaGuardia, Miami, Denver, San Francisco and Detroit), the airport data base is conceptually operable but not analytically precise. That is, the basic airport data are included but not to a fine level of detail. The data base is constructed, however, such that the data can be modified or additional data input in a relatively straightforward manner.

The major outputs of this program are as follows:

- The per passenger processing times (travel, service, delay, and total) at each landside service facility
- The per passenger processing times and cumulative processing times at each terminal unit and groundside area in the airport for both enplaning and deplaning passengers
- A summary of the delay and total processing times at the airport by terminal and for the entire airport.

Other outputs are also generated by the program; for example, the level of usage of each service facility is noted, and saturated facilities are flagged. Many other items are computed internally as discussed in Subsection 3.4, and if desired can be output without significant program modification.

This study demonstrates the feasibility of a concept, and should not be interpreted as the final assessment of airport landside congestion. It is believed that a major contribution has been made in this area. Even so, further development is required, particularly in the development of component models and overall program calibration and validation, before this program accurately assesses the airport landside congestion problem. On the basis of the research performed herein, the following recommendations are made for future study directly applicable to this program:

- Model Development. There are many interactions which complicate the description of any landside service. Additional effort in this area, particularly for deplaning passengers, could be directly applied to the existing program.

- Passenger Flow Study. A key element in this program is the specification of the passenger routes (e.g., percent who use ticketing). Although the flows used herein are generally accepted averages, a detailed examination of actual passenger behavior at each airport would be beneficial.

- Survey Additional Airports. The current airport data base should be expanded by surveying the large hub airports not already surveyed to ensure the accuracy of the results. The computer output, of course, can be no more accurate than the data input.

The following items are suggestions for uses of the landside analysis program:

- Determination of the passenger delays and total processing times at any airport for each terminal unit as a function of the forecasted enplanements. Identification of the major congestion areas and the demand level at which they become saturated. Investigation of the effects of alleviating the congestion through capital improvements and policy alternatives.

- Continuation of the above analysis by formulating a cost function which is a weighted sum of passenger delay ($/hr), capital improvement cost, and perhaps other variables. Determination of the alternatives which minimize this cost function.

- Comparison of the landside passenger delays with the airside delays experienced at large hub airports. Identification of airports where airside delays are less than, equal to, or greater than landside delays. Determination of a possible quantitative relationship between airside and landside delays at a particular airport or class of airports (say, by terminal type, runway configuration, etc.). Use of an airside delay model is required.

- Comparison of the results of the delays predicted by this program with the landside delays predicted by other methods (e.g., the Parson study (Reference 6) or the currently available Bechtel model (Reference 13)).

- Determination of the passenger delay as a function of time of day at a particular airport (or airports). This can be done by exercising the program for each separate hourly demand level. Quantitative determination of the delay level changes over time.

As discussed in Subsection 1.2, the landside analysis program is a third level delay model (steady-state demand); current airside delay models are fourth level (time-varying demand). A valid long-term goal is to develop a fourth level landside delay model to raise the landside state of the art to the airside modeling level.

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